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(54) **ARRAY ANTENNA HAVING MULTIPLE INDEPENDENTLY STEERED BEAMS**

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(22) Filed: **Jun. 26, 2000**

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(51) **Int. Cl.**[7] **H01Q 3/22**; H01Q 13/00
(52) **U.S. Cl.** **342/372**; 343/778
(58) **Field of Search** 342/372; 343/778

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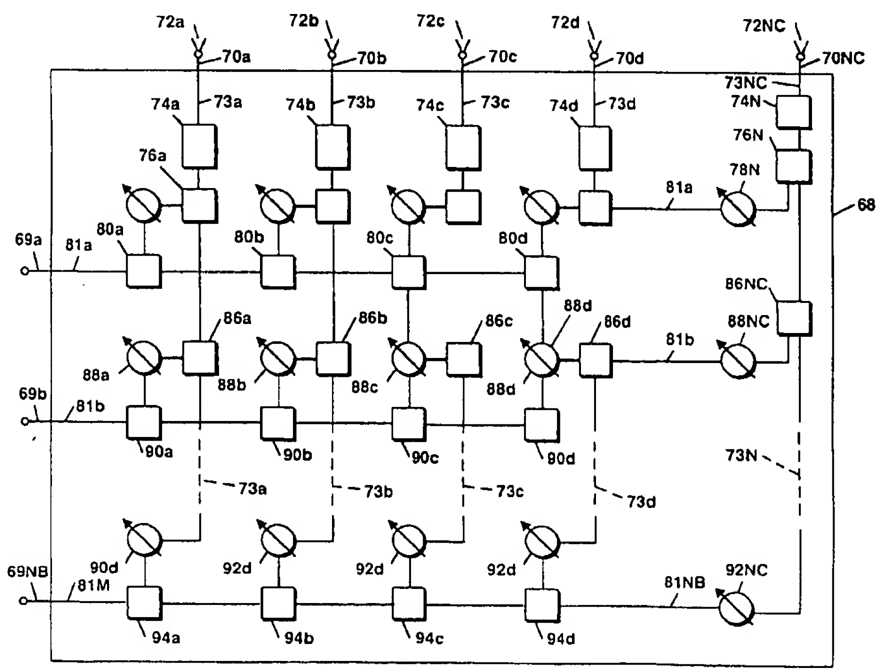
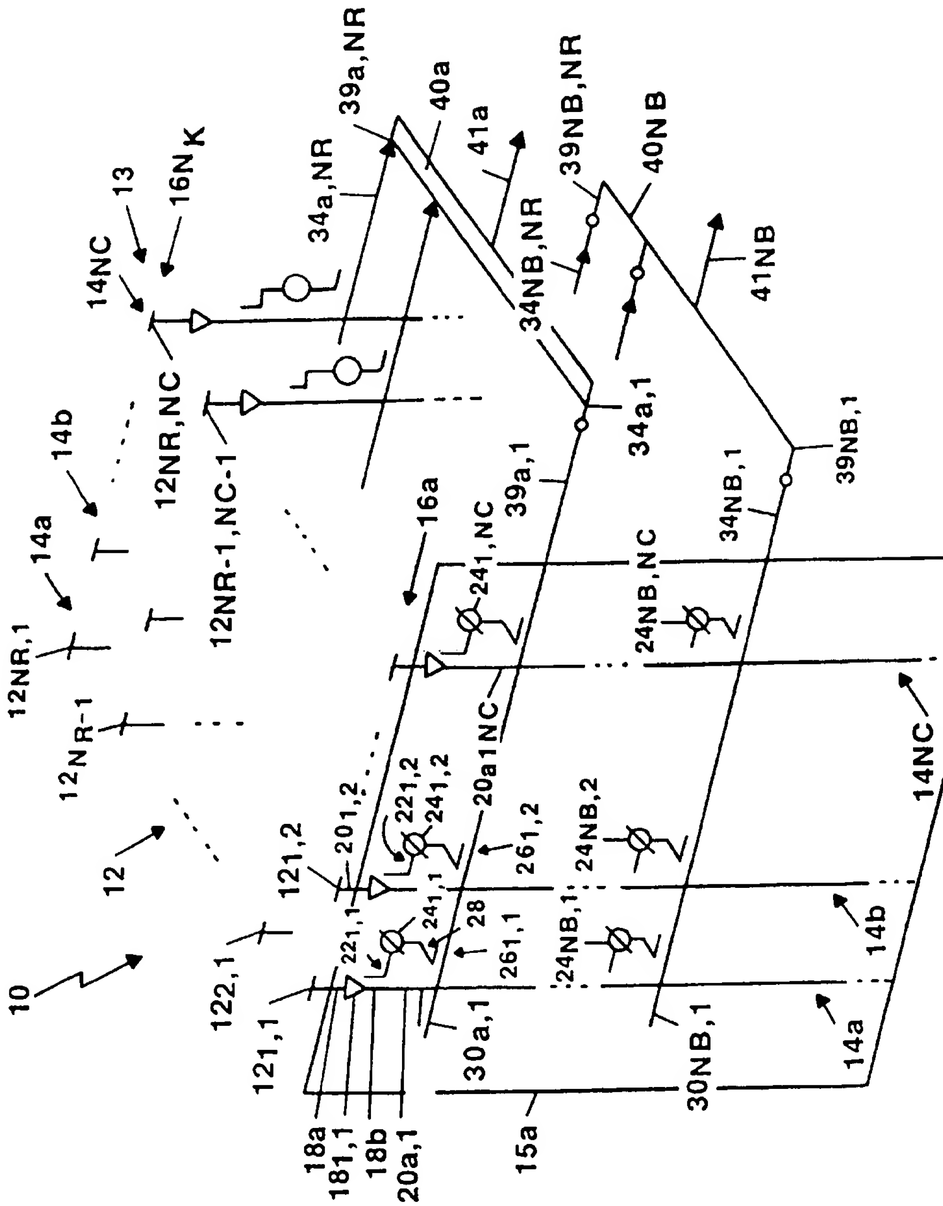
Primary Examiner—Mark Hellner
(74) *Attorney, Agent, or Firm*—Daly, Crowley & Mofford, LLP

(57) **ABSTRACT**

An array antenna system for forming multiple independently steered beams is described. The antenna system includes series or parallel feed circuits and phase shifters which are not disclosed directly in the signal path between the feed circuits and antenna elements included in the array antenna system.

9 Claims, 14 Drawing Sheets

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241,NC
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261,2
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Figure 1

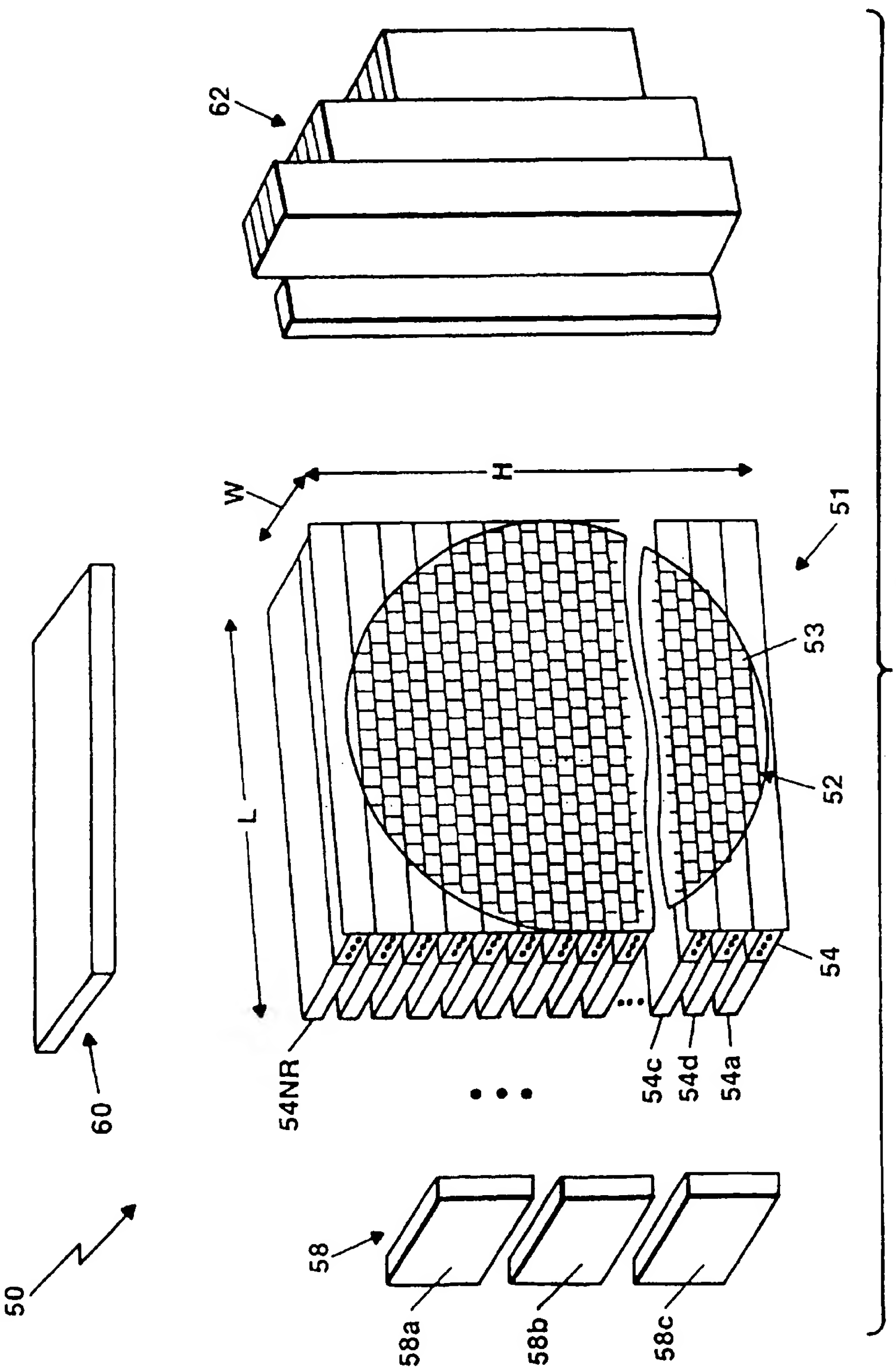


Figure 2

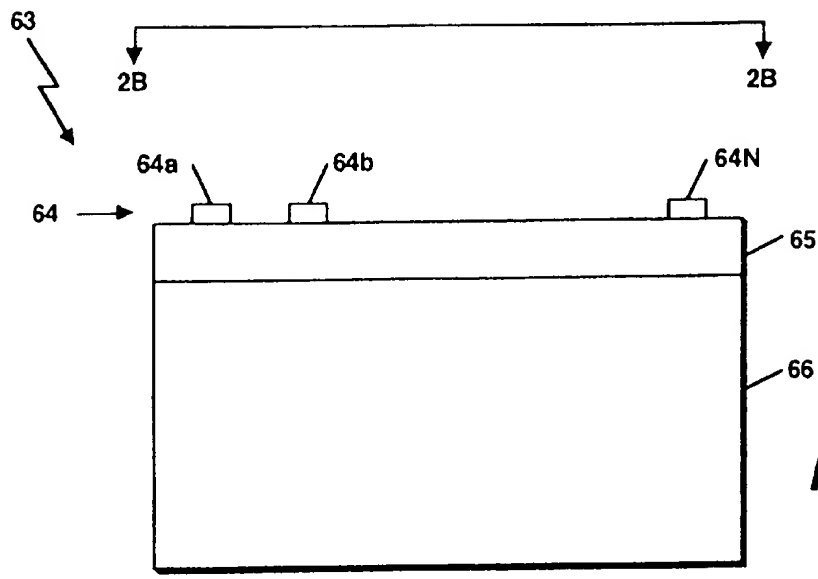


Figure 2A

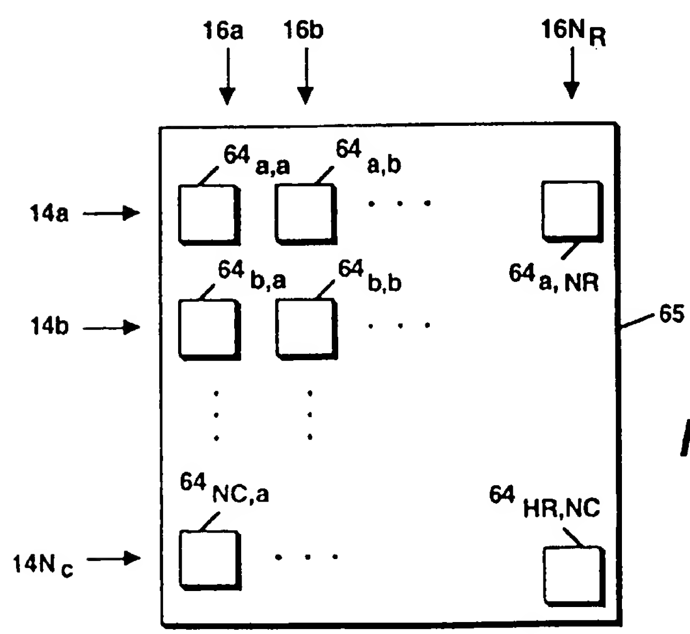
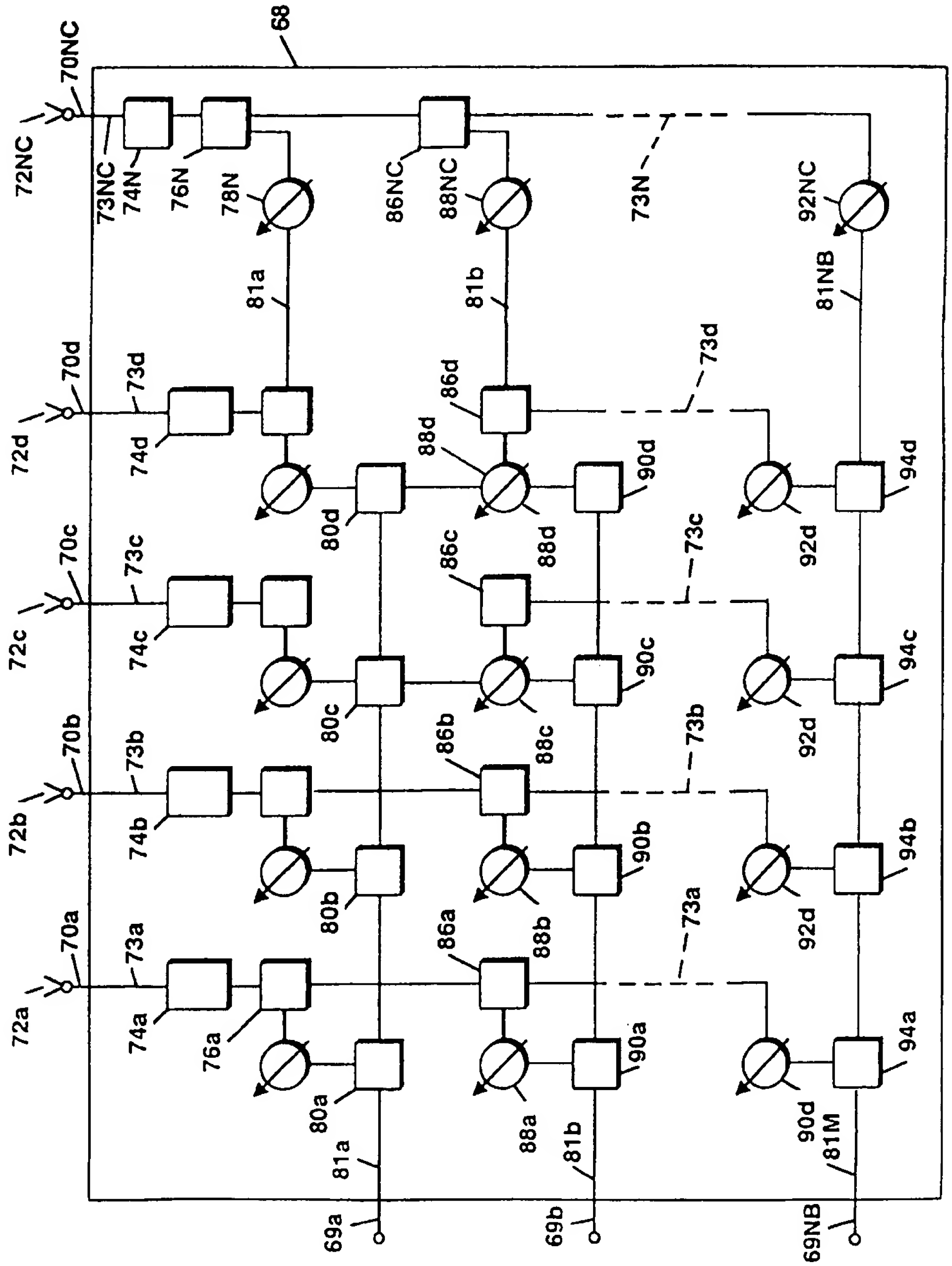


Figure 2B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80d
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92d
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70c
72c
73c
74c
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90c
94c
70b
72b
73b
74b
86b
88c
80b
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94b
70a
72a
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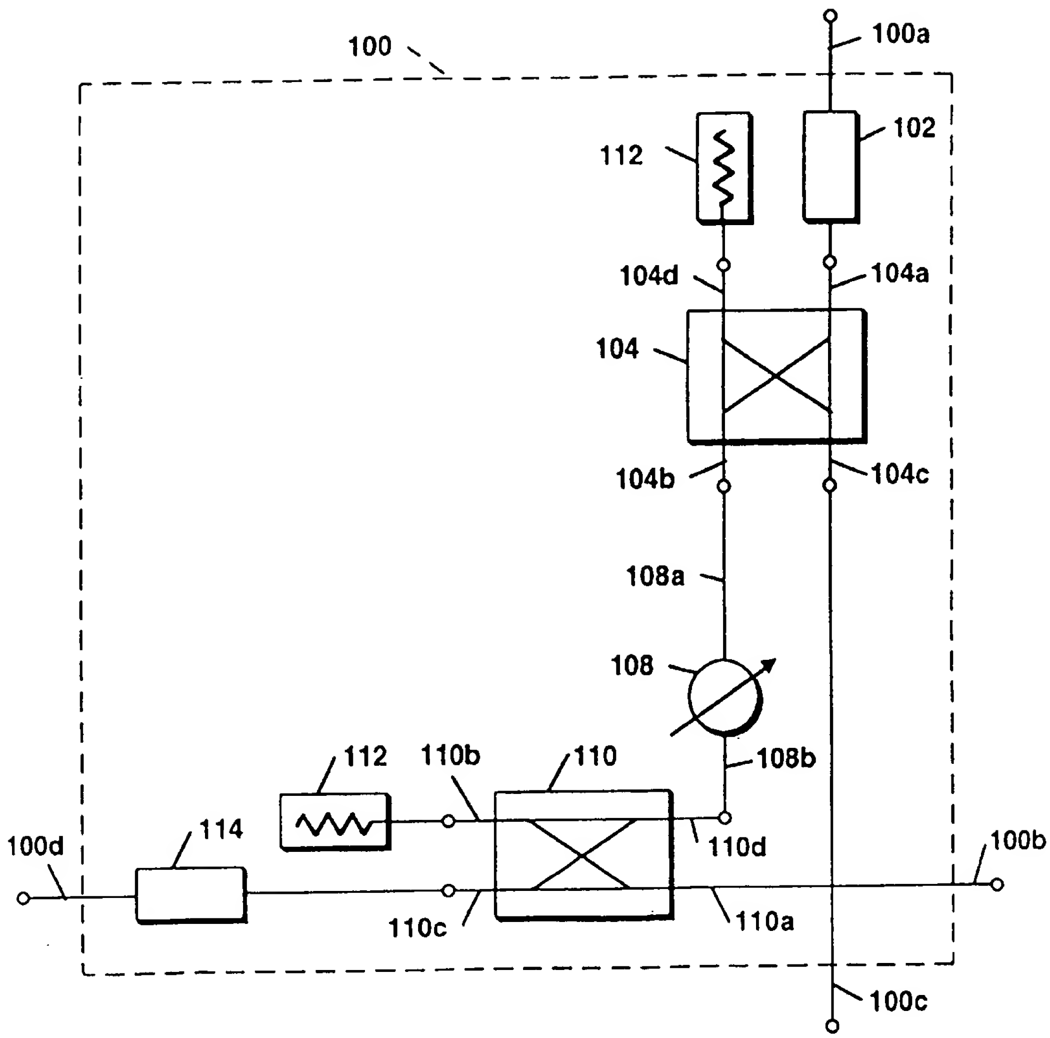
69b
69NB

Figure 3



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108b
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114
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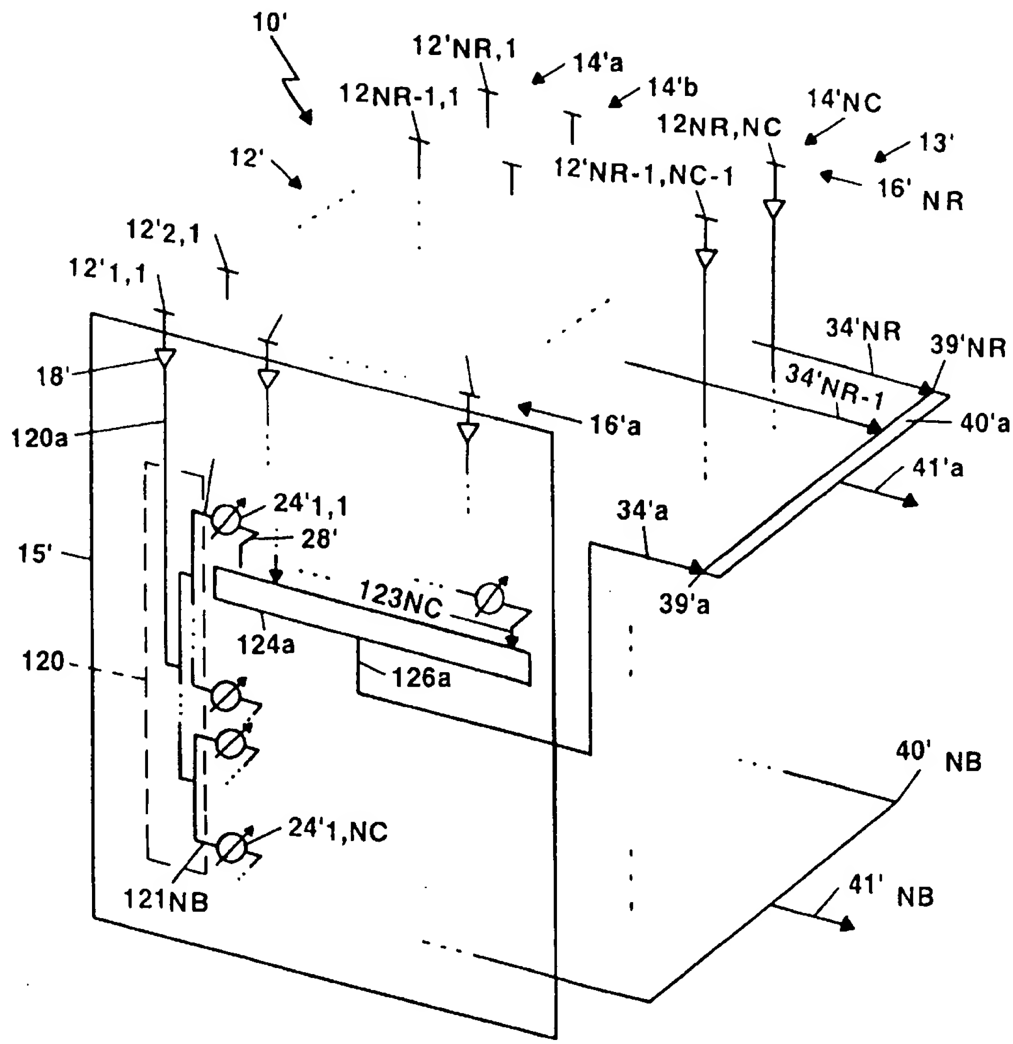
100c

Figure 4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14'b
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12NR,NC
13'
12'
12'NR-1,NC-1
16' NR
12'2,1
12'1,1
34'NR
39'NR
18'
34'NR-1
16'a
40'a
120a
41'a
24'1,1
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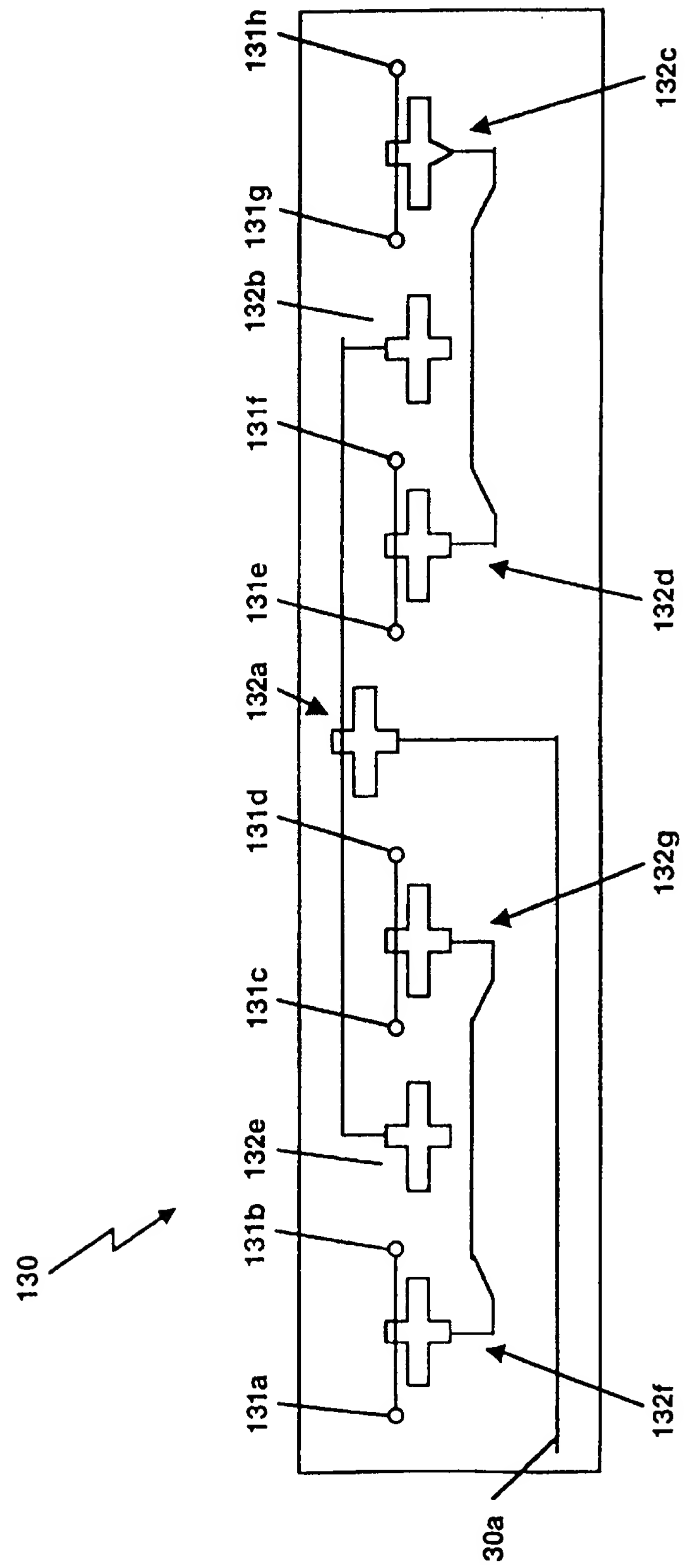
124a
120
126a
40' NB
24'1,NC
41' NB
121NB

Figure 5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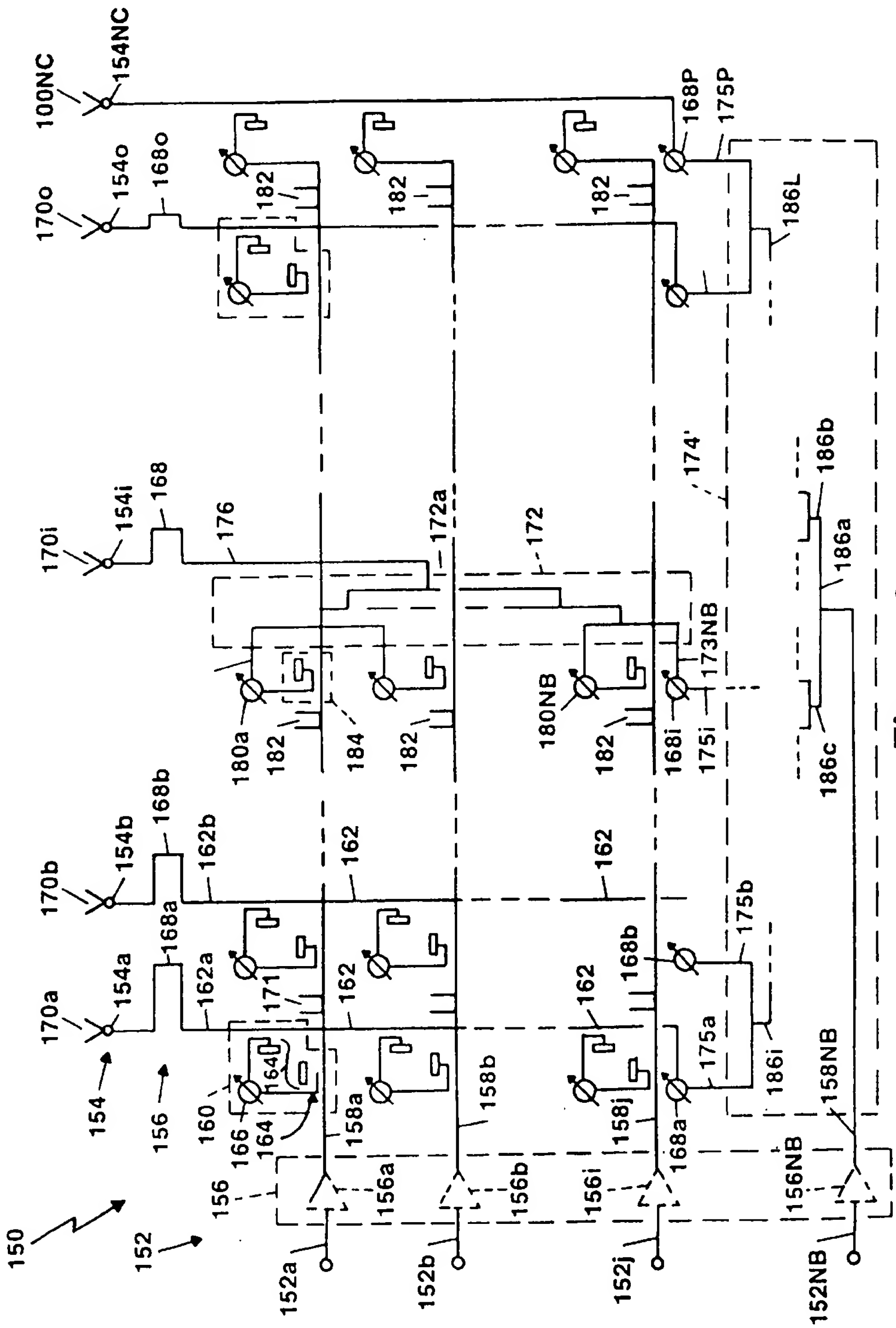
132f
130a

Figure 5A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168i
175i
186c
170b
154b
168b
162b
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154a
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175b
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154
156
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158j
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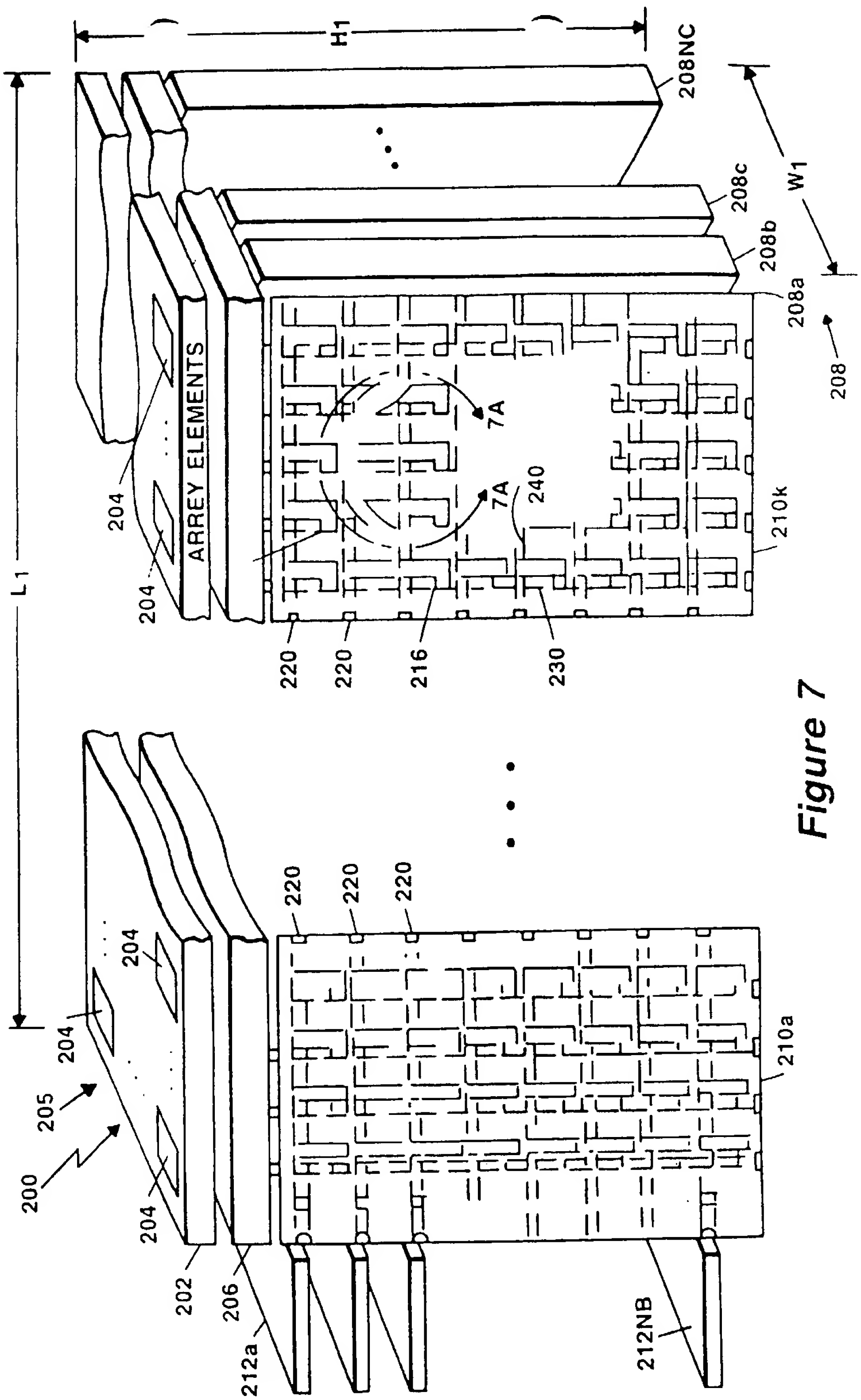
152b
152j
152NB

Figure 6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212NB
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220
210a

Figure 7

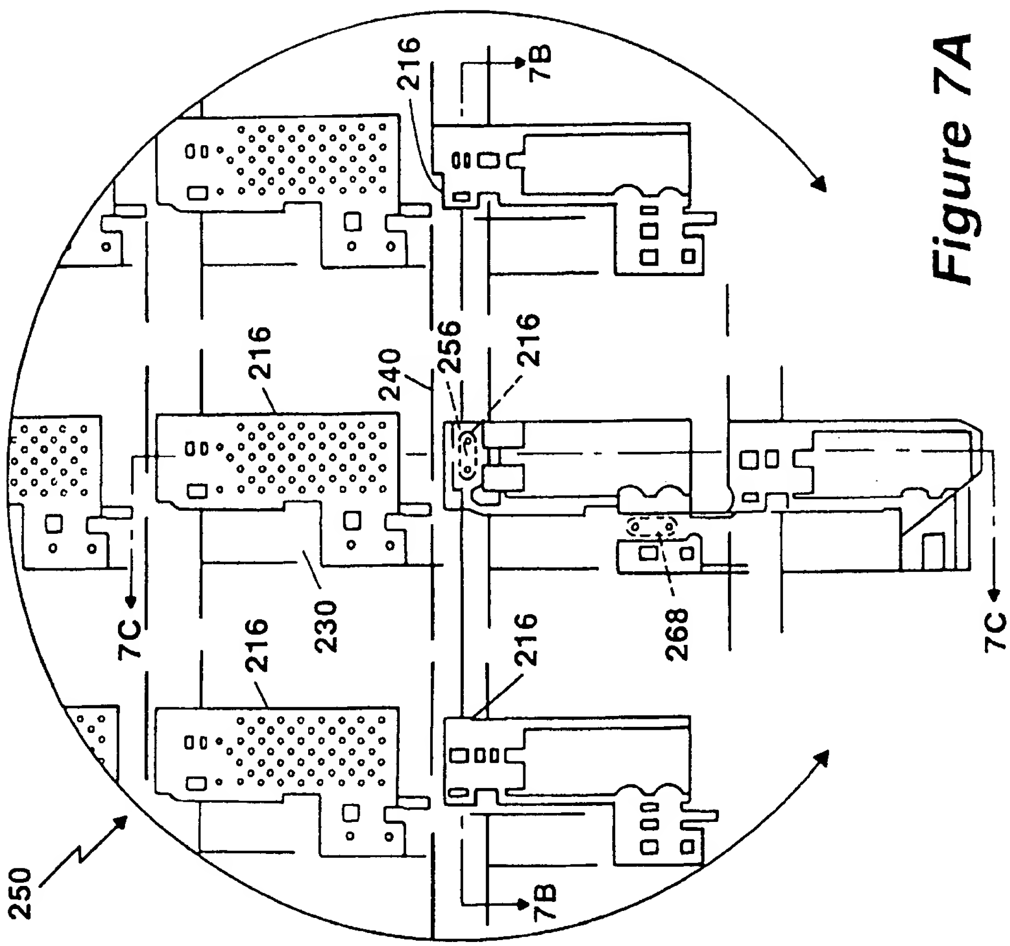

Figure 7A

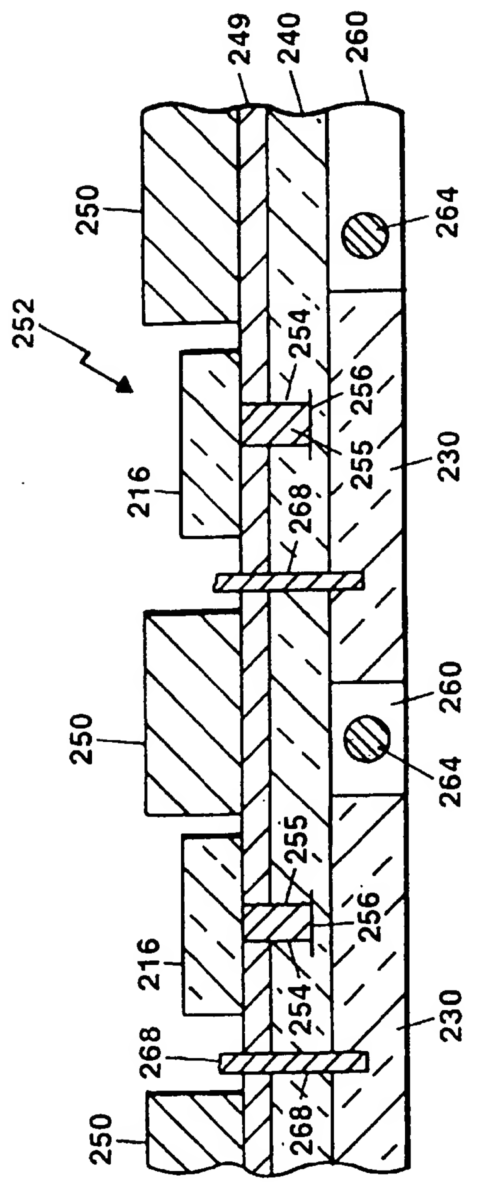

Figure 7b

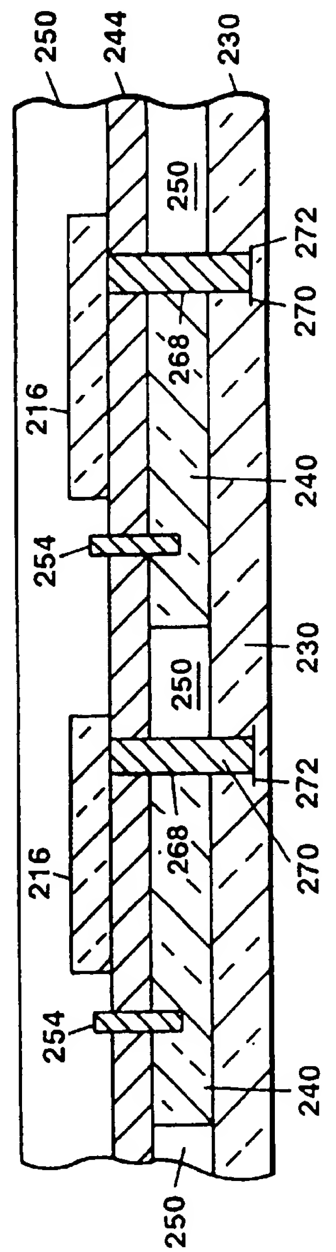

Figure 7c

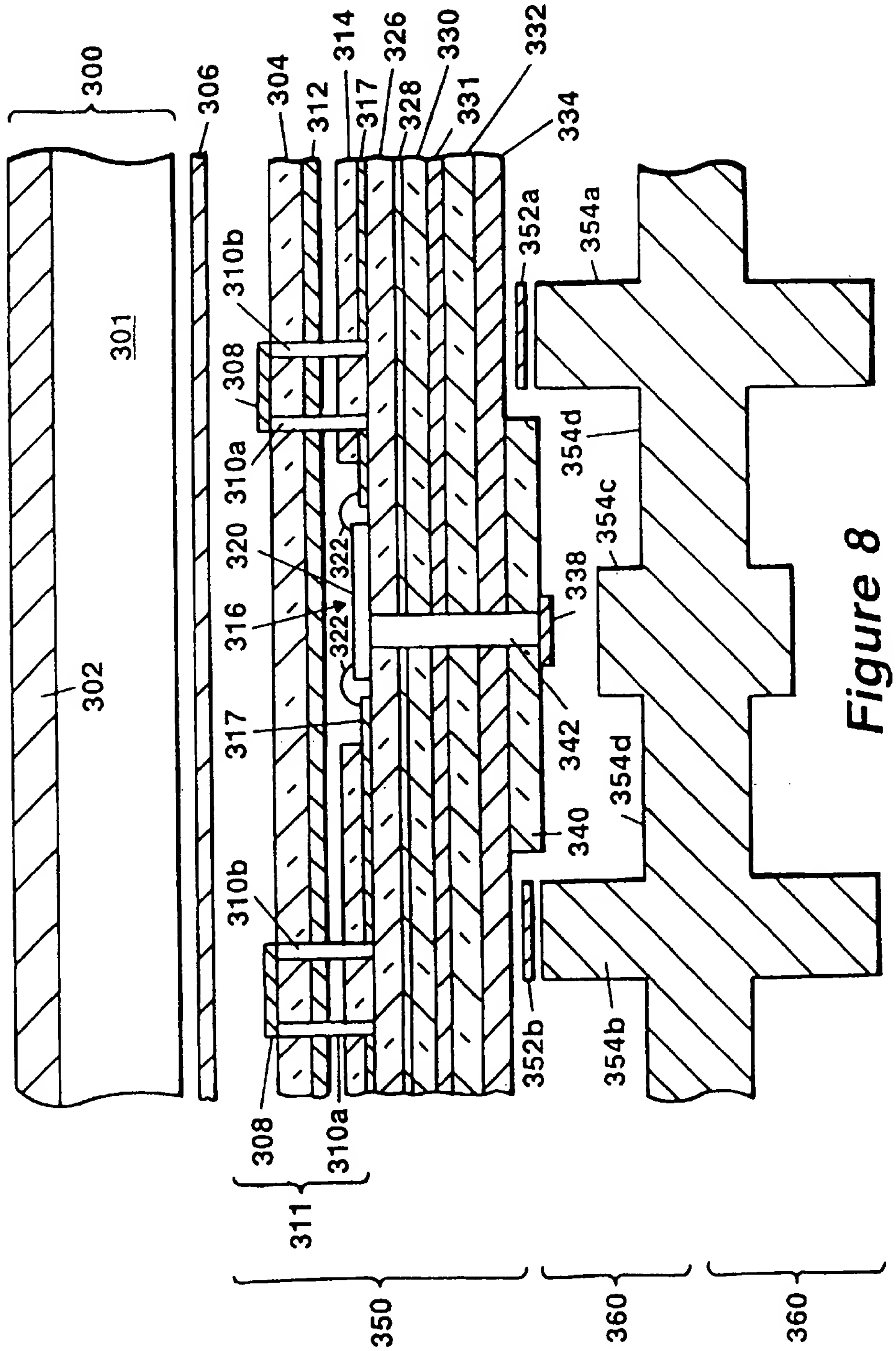
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Figure 8

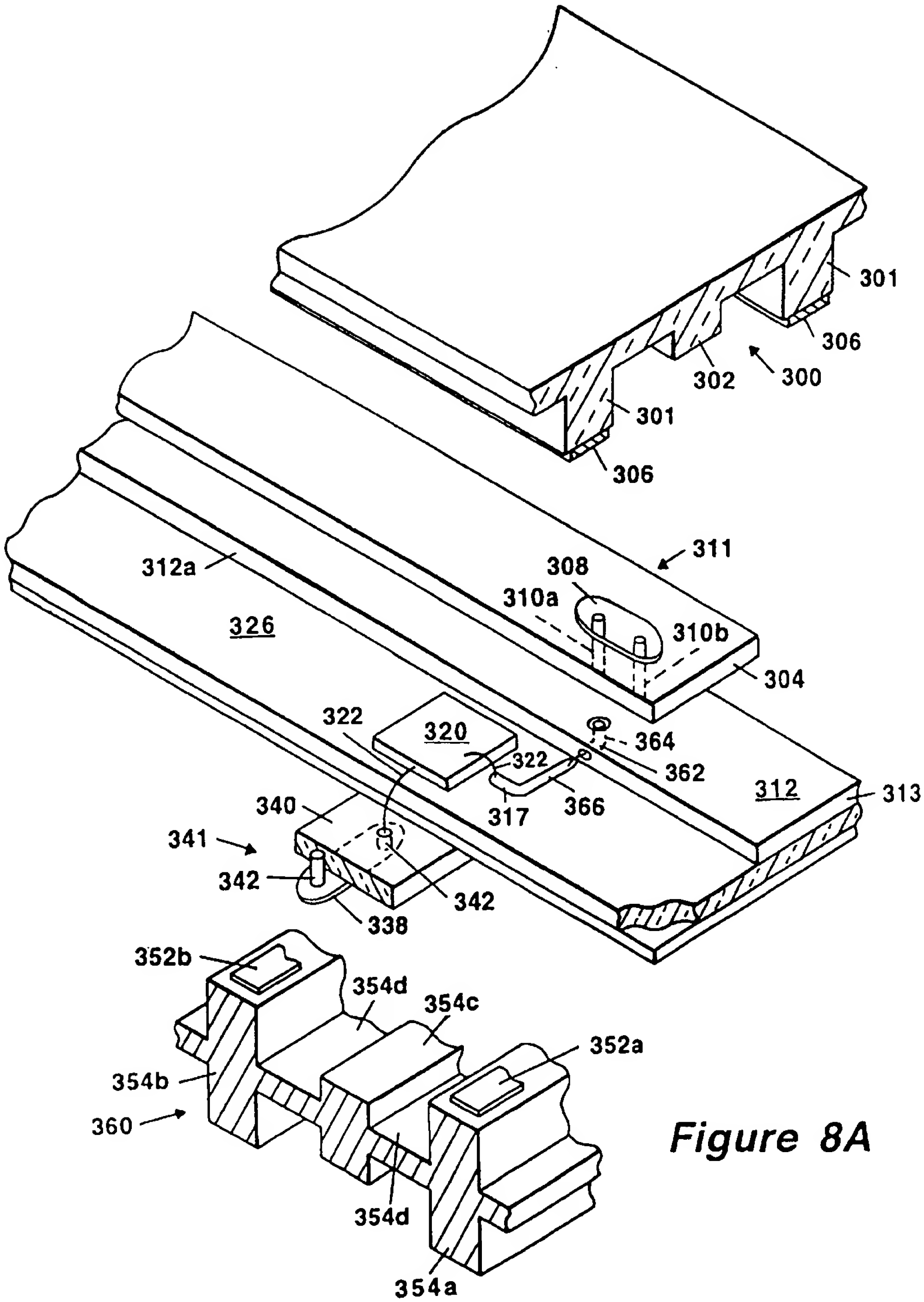
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Figure 8A

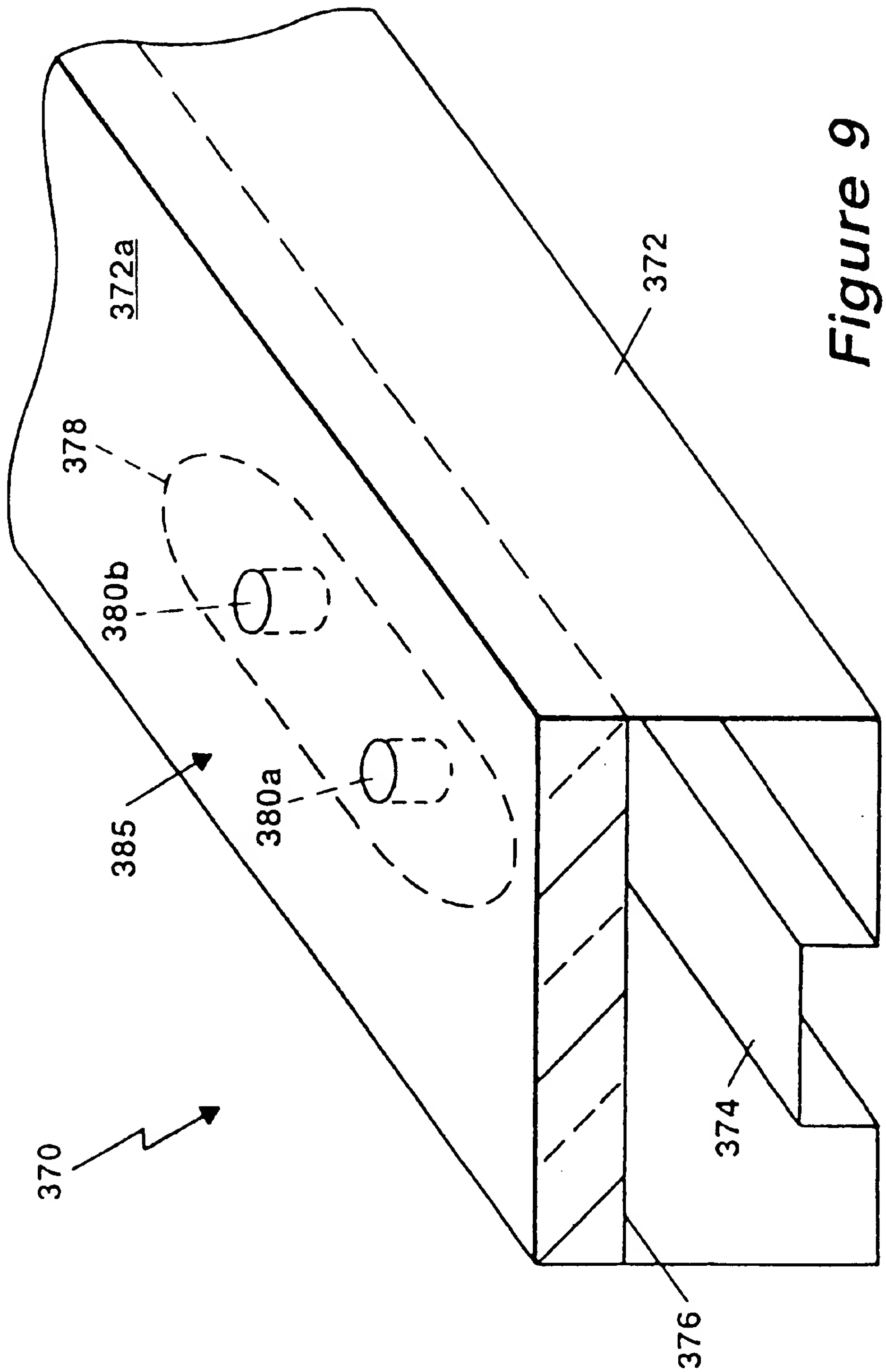

Figure 9

ARRAY ANTENNA HAVING MULTIPLE INDEPENDENTLY STEERED BEAMS

RELATED APPLICATIONS

This application is continuation of U.S. patent application Ser. No. 09/007,156, filed Jan. 14, 1998, now U.S. Pat. No. 6,104,343.

GOVERNMENT RIGHTS

Not applicable.

1. Field of the Invention

This invention relates generally to radio frequency (RF) antennas and more particularly to RF array antennas.

2. Background of the Invention

As is known in the art, a phased array antenna is a directive antenna made up of a plurality of individual radiating antenna elements, which generate a radiation pattern or antenna beam having a shape and direction determined by the relative phases and amplitudes of the excitation signal associated with the individual antenna elements. By properly varying the relative phases of the respective excitation signals, it is possible to steer the direction of the antenna beam. The radiating antenna elements may be provided as dipole antenna elements, open-ended waveguides, slots cut in waveguides, printed circuit antenna elements or any type of antenna element.

The array antenna thus includes of a number of individual radiating antenna elements suitably spaced with respect to one another. The relative amplitude and phase of the signals applied to each of the antenna elements are controlled to obtain the desired radiation pattern from the combined action of all of the antenna elements. Two common geometrical forms of array antenna are the linear array and the planar array. A linear array antenna includes a plurality of antenna elements arranged in a straight line in one dimension. A planar array antenna is a two-dimensional configuration of antenna elements arranged to lie in a plane. The planar array antenna may thus be thought of a linear array of linear array antennas.

The linear array antenna generates a fan beam when the phase relationships are such that the direction of radiation is perpendicular to the array. When the radiation is at some angle other than perpendicular to the array, the linear array antenna generates an antenna beam having a conical shape.

A two-dimensional planar array antenna having a rectangular aperture can produce an antenna beam having a fan-shape. A square or a circular aperture can produce an antenna beam having a relatively narrow or pencil shape. The array can be made to simultaneously generate many search and/or tracking beams with the same aperture.

One particular type of phased array antenna in which the relative phase shift between antenna elements is controlled by electronic devices is referred to as an electronically controlled or electronically scanned phased array antenna. Electronically scanned phased array antennas are typically used in those applications where it is necessary to shift the antenna beam rapidly from one position in space to another or where it is required to obtain information about many targets at a flexible data rate. In an electronically scanned phased array, the antenna elements, the transmitters, the receivers, and the data processing portions of the radar are often designed as a unit.

In some applications, it is desirable to provide an antenna system capable of producing multiple, independent antenna beams. Such antenna systems are advantageous in a variety of different applications such as communication satellites, ECM, ESM radar and shared aperture antennas used to accomplish simultaneously a combination of these functions. In communication satellite applications, for example, the simultaneous objectives of relatively high EIRP (Equivalent Isotropically Radiated Power) and G/T (Gain over System Temperature), wide access footprints, channelized operation and a high spectral efficiency (i.e., frequency reuse) leads to the need for multiple, independent antenna beams. It is relatively difficult to provide an electronically scanned phased array antenna capable of producing multiple independent antenna beams due to the interaction between the signals of the multiple antenna beams and the complexity of the multiple beamformer circuitry necessary to produce such multiple independent antenna beams.

The requirement for the phase array designer is made even more difficult when the operating frequency is selected to have a relatively high operating frequency in the frequency range of 20 to 30 GHz, for example, due to the corresponding decrease in the spacing between the antenna elements required for operation at that frequency. The problem is further exacerbated when it is desirable to provide a compact antenna system operating at a relatively high frequency range since the relatively small spacing between antenna elements and the need to couple feed circuits to the antenna elements result in difficult packaging requirements.

One approach to provide an antenna system having a relatively high operating frequency and multiple independent antenna beams is to utilize a lens or dish antenna which includes a separate feed circuit for each separate antenna beam. However, such an approach is relatively inflexible and it is relatively difficult to change the directions of the individual antenna beams. Thus, there is a significant interest in phased array antennas and in particular in electronically scanned phased array antennas.

It would, therefore, be desirable to provide an antenna capable of producing multiple independently steered antenna beams and which is compact, relatively low loss, and which consumes a relatively small amount of power. It would also be desirable to provide an electronically scanned phased array antenna capable of steering multiple independent antenna beams.

It would further be desirable to provide an electronically scanned phased array antenna in which failure of one phase shifter only affects one antenna beam and the one antenna element associated with the antenna beam. It would also be desired to provide an antenna in which there is no cascading of the amplitude and phase errors of phase shifters included in the phased array antenna.

SUMMARY OF THE INVENTION

In accordance with the present invention, an array antenna system for forming multiple independently steered beams includes an array of antenna elements, a first plurality of series feed signal paths each of the first plurality of series feed signal paths coupled to one of the antenna elements, a plurality of phase shifters each of the plurality of phase shifters having a first phase shifter port coupled to first ones of a plurality of couplers and with each of the first ones of the plurality of couplers disposed to couple a signal from a corresponding one of the first plurality of series feed signal paths and having a second phase shifter port coupled to second ones of the plurality of couplers with each of the second ones of the plurality of couplers disposed to couple a signal from the second phase shifter ports to a corresponding one of a second plurality of series feed signal paths and

a signal combiner for combining the signals to provide one or more antenna beams.

With this particular arrangement, an antenna capable of providing multiple independent antenna beams is provided. The antenna may be provided as an electronically controlled phased array antenna which includes an electronic device for controlling a relative phase shift between antenna elements such as electronically controlled phase shifters. By disposing the phase shifters such that they are not directly in the antenna element feed circuit signal paths, the phase shifter settings for the i^{th} beam are independent of that from the j^{th} beam. The failure of one phase shifter only effects a single beam as a failure of only one element. Furthermore, the phase shifter amplitude and phase errors as well as losses do not cascade. Moreover, the signal from one antenna element propagates through only one phase shifter to form the antenna beam before the signals for that antenna beam are summed. Hence, the antenna is provided as a relatively low loss antenna. Finally, by appropriately arranging phase shifters and couplers in the feed circuit, coupling between the multiple antenna beams is minimized. That is, the power from beam the i^{th} does not couple to beam the j^{th} as it does in prior art techniques. It should be noted that the technique may be used to provide both receive and transmit array antenna systems.

In accordance with a further aspect of the present invention, an array antenna system for forming multiple independently steered beams includes an array of antenna elements, a first plurality of parallel feed signal paths each of the first plurality of parallel feed signal paths coupled to one of the antenna elements, a plurality of phase shifters each of the plurality of phase shifters having a first phase shifter port coupled to predetermined ones of the first plurality of parallel feed signal paths and having a second phase shifter port coupled to second plurality of parallel feed signal paths. Each of the second plurality of parallel feed signal paths coupled to a corresponding one of a plurality a signal combiners for combining the signals to provide one or more antenna beams.

With this particular arrangement, an antenna capable of providing multiple independent antenna beams is provided. The parallel feed signal paths may be provided as corporate power dividers or series feed lines and signal combiners. The antenna may be provided as an electronically controlled phased array antenna which includes electronically controlled phase shifters. By disposing the phase shifters such that they are not directly in the antenna element feed circuit signal paths, the phase shifter settings for the i^{th} beam are independent of that from the j^{th} beam. The failure of one phase shifter only effects a single beam as a failure of only one element. Furthermore, the phase shifter amplitude and phase errors as well as losses do not cascade. Moreover, the signal from one antenna element propagates through only one phase shifter to form the antenna beam before the signals for that antenna beam are summed. Hence, the antenna is provided as a relatively low loss antenna. Finally, by appropriately arranging phase shifters and parallel signal divider circuits in the feed circuit, coupling between the multiple antenna beams is minimized. That is, the power from beam the i^{th} does not couple to beam the j^{th} as it does in prior art techniques. It should be noted that the technique may be used to provide both receive and transmit array antenna systems.

In accordance with a still further aspect of the present invention, in one particular embodiment a beam/element grid junction for use in a phased array antenna includes a first directional coupler having a first port, a second port, a

third port and a fourth port, a phase shifter having a first port coupled to the third port of the directional coupler and having a second port and a second directional coupler having a first port coupled to the second port of the phase shifter and having a second port, a third port and a fourth port. With this particular arrangement, the beam/element grid junction can be coupled to an antenna element feed circuit such that phase shifter is not directly in the antenna element feed circuit signal path. Thus, the phase shifter setting for one antenna element in an array of antenna elements can be controlled independently of the phase shifter settings for the other antenna elements in the array. The beam/element grid junction may thus further include an antenna element coupled to a first port of the first directional coupler and a transmitter can be coupled to a first port of the second directional coupler to provide a transmit system. Alternatively or in addition to the transmitter coupled to the second directional coupler, a signal combiner can be coupled to a second port of the second coupler and a receiver can be coupled to an output port of the signal combiner. With this arrangement a transmit/receive or a receive only system can be provided.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing features of this invention as well as the invention itself may be more fully understood from the following detailed description of the drawings in which:

FIG. 1 is a schematic diagram of a multi-beam system using series feeds and parallel phase shifters to form independently steered antenna beams;

FIG. 2 is a block diagram of an array antenna which provides multiple independently steered antenna beams;

FIG. 2A is a diagrammatical view of a row board of the antenna used in FIG. 2;

FIG. 2B is a top view taken along lines 2B—2B of FIG. 2A;

FIG. 3 is a schematic diagram of a beamformer board for use in a transmit antenna system;

FIG. 4 is a schematic diagram of a beam/element grid junction;

FIG. 5 is a schematic diagram of a receive multi-beam antenna system using corporate combiners and parallel phase shifters to form multiple independently steered antenna beams;

FIG. 5A is a diagrammatical view of a power divider circuit which may be used in the antenna system of FIG. 5;

FIG. 6 are schematic diagrams of a single antenna row board having both series and corporate feed structures;

FIG. 7 is a block diagram of an antenna array including series feed circuits which provides multiple independently steered antenna beams;

FIG. 7A is an enlarged portion of the antenna array taken along lines 7A—7A of FIG. 7;

FIG. 7B is a cross-sectional view of the antenna array taken along lines 7B—7B in FIG. 7A;

FIG. 7C is a cross-sectional view of the antenna array taken along lines 7C—7C in FIG. 7A;

FIG. 8 is a cross-sectional view of a beamformer;

FIG. 8A is a perspective view of a beamformer; and

FIG. 9 is a perspective view of a waveguide coupler.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to FIG. 1, a two-dimensional phased array antenna system 10 capable of forming a plurality (e.g., 64)

of independently steered antenna beams includes a plurality of antenna elements generally denoted **12** disposed to here provide a planar array antenna **13**. The antenna system **10** includes array columns $1a$–$14N_c$ generally denoted **14** and array rows $16a$–$16N_R$ generally denoted **16**. The plurality of antenna elements **12** are thus arranged as an array having N_C columns and N_R rows (FIG. 2B). Using the above notation, the antenna element located at the intersection of the first position in the first column **14***a* and the first position in the first row **16***a* is thus denoted $12_{1,1}$ and the antenna element located at the intersection of the last position of the last column $14N_C$ and the last position of the last row $16N_R$ is denoted $12_{NR,NC}$.

It should be noted that although the description provided hereinbelow describes the inventive concepts in the context of a planar array antenna **13**, those of ordinary skill in the art will appreciate that the concepts equally apply to other types of array antennas including, but not limited to, arbitrary shaped planar array antennas as well as cylindrical, conical, spherical and arbitrary shaped conformal array antennas. Also, reference is sometimes made herein to generation of an antenna beam having a pencil shape. Those of ordinary skill in the art will appreciate, of course, that antenna beams having other shapes may also be used and may be provided using well-known techniques such as by inclusion of attenuators into appropriate locations in a feed circuit, for example.

To form an output signal for a first antenna beam (referred to herein as beam 1) an output port of the antenna element $12_{1,1}$ is coupled to a row board **15***a*. Row board **15***a* includes an amplifier **18** which may be provided, for example, as a low noise amplifier (LNA) $18_{1,1}$ at an input port **18***a*. An output port **18***b* of LNA $18_{1,1}$ is coupled to a first series feed signal path $20_{a,i}$. Thus, LNA **18** receives a signal from the antenna element $12_{1,1}$ and provides an amplified signal to the series feed signal path $20_{a,1}$.

Series feed signal path $20_{a,1}$ may be provided as a stripline transmission line, a microstrip transmission line, an air or dielectric filled waveguide transmission line disposed over a conducting plane, a ridge waveguide transmission line or any other type of transmission line which may be provided using any technique well known to those of ordinary skill in the art to provide a signal path transmission line. The particular manner in which the signal path $20_{a,1}$ is provided will be selected in any particular application after consideration of a variety of factors including but not limited to the desired operating frequency of the antenna, the ease with which a particular technology can be manufactured, transmission line insertion loss, bandwidth of the signals, as well as the size, weight and cost of materials and fabrication of a particular type of transmission line.

A first coupler $22_{1,1}$ couples a portion of the signal propagating along series feed signal path $20_{a,1}$ and to a first or input port of a phase shifter $24_{1,1}$. Phase shifter $24_{1,1}$ introduces into the signal fed thereto a predetermined phase shift $\emptyset_{1,1}$.

A second or output port of phase shifter $24_{1,1}$ is coupled through a second coupler $26_{1,1}$ to a second series signal path $30_{a,1}$. Signal path $30_{a,1}$ may be provided as the same type or a different type of transmission line as signal path $20_{a,1}$. In some embodiments, series feed signal paths $20_{a,1}$, $30_{a,1}$ are disposed on different layers of the same printed circuit board **15***a*. Thus, in this case an RF feedthrough **28** couples the signal from a layer of the printed circuit board on which series feed signal path $20_{a,1}$ is disposed to a layer of the printed circuit board on which series feed signal path $30_{a,1}$ is disposed. Similarly, an RF feedthrough or other coupling means would be required if signal paths $20_{a,1}$, $30_{a,1}$ were disposed on different printed circuit boards (PCBs) rather than different layers of the same PCB.

In this particular embodiment, the feed circuits $20_{a,1}$, $30_{a,1}$ are orthogonally disposed with the first feed circuit **20** here being shown having a generally vertical direction and the second feed circuit here being shown having a generally horizontal direction. It should be appreciated, however, that the relative physical positions between the two signal path feed circuits $20_{a,1}$, $30_{a,1}$ need not be orthogonal or have any other particular physical relationship.

The output from phase shifter $24_{a,1}$ is coupled through a coupler $26_{1,1}$ to the signal path feed circuit $30_{a,1}$ which contributes to the formation of a first fan beam (i.e. fan beam number **1**) at port $34_{a,1}$.

In a similar manner, the output from the second antenna element $12_{1,2}$ of row board **15***a* is fed to the input port of a low noise amplifier (LNA) $18_{1,2}$. The LNA $18_{1,2}$ is followed by a second vertically oriented series feed signal path $20_{a,2}$. The signal from the series feed signal path $20_{a,2}$ is in turn coupled through a coupler $22_{1,2}$ to a phase shifter $24_{1,2}$ where it receives the phase shift $\emptyset_{1,2}$. The output of the phase shifter $24_{1,2}$ is in turn coupled (through the second layer of the row board **15***a* if necessary) to the series feed signal path $30_{a,1}$.

In a similar manner, the outputs of the other antenna elements $12_{1,3}$–12_{NC} of row board **15***a* are coupled into this same horizontally running series feed signal path $30_{a,1}$ (i.e. series feed signal path number 1) to provide the signal at output port $34_{a,1}$ which forms a first fan beam (i.e. fan beam number **1** for forming pencil beam 1). The other boards, $15b$–15_{NR}, provide similar output signals $34_{a,2}$–$34_{a,NR}$, forming fan beams for forming beam number **1** with each such output signals pointing in the same direction.

Next, the output signals at ports $34_{a,2}$–$34_{a,NR}$ are fed to respective input ports $39_{a,1}$–$39_{a,NR}$ of a signal combiner **40***a*. In some embodiments, it may be desirable to provide signal combiner **40***a* as an isolating signal combiner which includes isolating resistors to isolate the input ports $39_{a,1}$–$39_{a,NR}$ from each other. Signal combiner **40***a* combines the individual fan beam signals fed thereto and provides an output signal at a signal combiner output port **41***a*. This is a pencil beam output for beam **1**.

In a similar manner signals from antenna elements $12_{1,1}$–$12_{1,NC}$ are coupled through respective ones of first series feed signal paths $20_{a,2}$–$20_{a,NC}$ to respective ones of second series feed signal paths $30_{b,1}$–$30_{NB,1}$. The signals coupled to series signal paths $30_{b,1}$–$30_{NB,1}$ propagate toward output ports $34_{b,1}$–$34_{NB,1}$ respectively, to provide at output ports $34_{b,1}$–$34_{NB,1}$ the signals which form fan beams 2-N_B for forming pencil beams 2-N_B.

The remaining rowboards 15_b–15_{NR} coupled to respective antenna element rows 16_b–16_{NR} provide similar output signals $34_{b,1}$–$34_{b,NR}$ … $34_{NB,1}$–$34_{NB,NR}$ for fan beams 2-N_B with each such output signal for a given beam pointing in the same direction but each beam possibly pointing in a different direction (where N_B equals 64 for example) are formed as shown in FIG. **1**.

It should be noted that the antenna architecture described above in conjunction with FIG. **1** has the advantage that the phase settings for each of the phase shifters 24_{ij} in the antenna system **10** for beam i is independent of the phase shifter settings for beam j. Also, since the phase shifters 24_{ij} are not coupled in series, the antenna architecture of FIG. **1** has the advantage that the phase shifter amplitude and phase errors as well as insertion losses do not cascade.

To form an antenna beam, the signal from one antenna element (e.g. antenna element $12_{1,1}$) propagates through only one phase shifter (e.g. phase shifter $24_{NB,1}$) before the signal is summed to form an antenna beam (e.g. antenna beam N_B). Furthermore, the antenna architecture of FIG. 1 results in an antenna system having relatively low insertion loss characteristics since each signal incurs the losses associated with only a single phase shifter **24**. The antenna architecture of the present invention also provides the advantage that the failure of one of the phase shifters **24** only effects a single beam in the same manner that the failure of a single one of the plurality of antenna elements effects an antenna beam. Finally, the antenna architecture described above results in an antenna system in which there is no coupling between multiple antenna beams. That is, the power from beam i does not couple into beam j as it does in other implementations.

Although the implementation described above is for an array antenna operating in a receive mode, the concepts and techniques described above can also be used to provide an array antenna operating in a transmit mode as will be described below in conjunction with FIG. **3**.

It should also be noted that the i^{th} beam (out of a possible N_B beams) and therefore the j^{th} row (i.e. the j^{th} row board out of N_R possible row boards) is pointing in the same direction as the i^{th} beam for all the other rows. That is, the i^{th}-beam for each of the rows **15***a*–15_{NR} are steered to the same angle. For convenience and ease of explanation, this steering direction will be referred to herein as the azimuth direction. The k^{th} beam could be pointing in a different or the same direction as the i^{th} beam.

The i^{th} beam output signals provided at the output port of each of the row boards 16_a–16_{NR}, are combined to form the i^{th} pencil beam from the fan beams of each row (or row board). Towards this end the phase shifters 24_{ij} forming the i^{th} beam for the first board are incremented to provide a phase shift setting for the second board **16***b*. Specifically, all the phase shifters $24_{1,1}$ to $24_{1,Nc}$ having phase shifter settings $Ø_{11}$ to $Ø_{1,NC}$ are shifted nominally by a predetermined phase $\Delta\theta_1$ to steer the beams in the elevation direction. The phase shift $\Delta\theta_1$ nominally would be the same for $Ø_{11}$ to $Ø_{1,NC}$

It should be noted that the steering actually occurs in sine space rather than in Az-El space, but for simplicity and ease of explanation, the operation will be described as if occurring in Az-El space. Successive rows **16***b*–$16N_R$ receive the same increase in phase shift $\Delta\theta$, for beam **1** in going from one board to the next. In this way, beam steering to a specified elevation angle is accomplished. As mentioned above, the phase shift $\Delta\theta_1$ nominally could be the same for $Ø_{11}$ to $Ø_{1,NC}$. However, to shape beam **1** in the elevation direction a different $\Delta\theta_1$, $\Delta\theta_{1,NC}$ could be used for each column.

In one particular embodiment, each row board **15** in the array antenna system **10** is provided from a multilayer printed circuit board. Each row board **15***a*–15_{NR} includes circuitry to receive signals from antenna elements **12**, and introduces a particular phase shift into each of the signals before combining the signals to form a plurality, here N_B, fan antenna beams from the N_C antenna elements of each row. In one particular embodiment, the number of fan beams N_B is chosen to be 64. Those of ordinary skill in the art will appreciate of course that any compatible number of antenna elements and fan beams can be used.

Referring now to FIG. **2**, an antenna system **50** includes an array antenna **51** having an array aperture **52**. In this particular example, the array aperture **52** is provided having a circular shape. It should be appreciated of course that other aperture shapes including rectangular, square or irregular aperture shapes may also be used. The array antenna **51** is provided from a plurality of beamformer row boards **54***a*–$54N_R$ each of the beamformer row boards **54** coupled to corresponding ones of a plurality of antenna elements **53**.

A drive column board assembly **62** is coupled to the beamformer row boards **54** to receive signals from and provide signals to the row boards **54**. In a receive mode of operation the drive column boards **62** receive signals from the beamformer row boards **54** and form a receive antenna beam. In a transmit mode of operation, drive column boards **62** provide signals having predetermined amplitudes and phases to the row boards **54**. Once the row boards **54** receive the signals, the final phase shift is done via phase shifters disposed on the row boards **54**.

Also coupled to phased array antenna **51** are one or more DC-to-DC converters **58***a*–**58***c* generally denoted **58**. DC-to-DC converters provide appropriately conditioned and filtered DC power signals to those circuit components in the antenna array **51** which require DC power. For example, phase shifters **24** and amplifiers **18** described above in conjunction with FIG. **1** may require DC power. If antenna **51** does not require DC power or if no conversion of DC power is necessary, converters **51** may be omitted.

An array controller **60** is also coupled to the array antenna **51** to thus provide logic signals which control phase shifter settings and in some cases amplitude adjustment circuits thereby controlling the radiation pattern and pointing direction of antenna beams produced by antenna **51**. Amplitude adjustment circuits may be used to provide the antenna beam having any shape other than a pencil shape.

Referring now to FIGS. **2A**, **2B** in which like elements are provided having like reference designations, a beamformer row board **63** is shown having a plurality of antenna elements **64***a*–**64**N generally denoted **64** disposed thereon. Antenna elements **64** may be provided for example as aperture antenna elements which may be provided from waveguide apertures or from printed circuit antenna elements or dipole elements or notch radiator elements. In one embodiment, antenna elements **64** may be provided as printed circuit aperture antenna elements such as microstrip dipole or microstrip patch antenna elements. Those of ordinary skill in the art will appreciate of course that antenna elements **64** may also be provided from any other type of antenna element well known to those of ordinary skill in the art.

The particular type of antenna element selected for any particular application depends upon a variety of factors including but not limited to the number of antenna elements included in the antenna array, the element peak power, bandwidth needed, volume and weight constraints, operating temperature and environment, the operating frequency of the antenna array (which affects the physical size of each individual antenna element and the physical spacing between antenna elements in the antenna array), the difficulty in manufacturing the particular type of antenna element, the performance characteristic of the antenna element and the desired performance characteristic of the array antenna.

In the embodiment shown in FIGS. **2A**, **2B** the antenna elements **64** are disposed over a first surface of a first substrate **65**. A second surface of substrate **65** is disposed over a second substrate **66**. Substrate **66** can be similar to row boards **15** described above in conjunction with FIG. **1**

and thus includes antenna element feed circuitry which may, for example, be similar to the feed circuitry described above in conjunction with FIG. 1. The feed circuitry on substrate **66** is electrically coupled to the antenna elements **64**. In some implementation the elements of the i^{th} row will be part of the i^{th} row board. For example, in some embodiments it may be advantageous to provide the antenna elements **64** as an integral part of the substrate **66** in which case substrate **65** can be omitted.

Although the antenna elements **64** are here shown having a square shape, those of ordinary skill in the art will also appreciate that the antenna elements **64** may be provided having a rectangular shape, a circular shape, or any other shape including irregular shapes from which an antenna element may be provided. It should be noted that additional circuit board layers would be needed for each row board to provide the control lines and power lines for any circuit component on board **66** which requires DC power and control logic signals.

Referring now to FIG. **3**, a beamformer board **68** for use in a transmit antenna system incudes a plurality of beamports **69***a*–**69**NB and a plurality of antenna element ports **70***a*–**70**NC each having a respective one of a plurality of antenna elements **72***a*–**72**NC coupled thereto. Beamformer board **68** further includes a plurality of series antenna element feed signal paths **73***a*–**73**NC generally denoted **73** and a plurality of serial beamformer feed signal paths **81***a*–**81**NB generally denoted **81**. The signal path from beamport **69***a* to antenna element **72***a* is representative of the signal paths from each of the beamports **69***b*–$69N_B$ to each of the antenna elements **72***b*–**72**NC.

A signal is fed through beamport **69***a* through series signal path **81***a* to a first coupling device **80***a*. A portion of the signal is coupled through coupling device **80***a* to a first port of a phase shifter **78***a*. Phase shifter **78***a* introduces a predetermined phase shift to signals fed thereto and provides a phase shifted output signal to a second coupling device **76***a*. Coupling device **76***a* couples a portion of the phase shifted signal from the phase shifter **78***a* to an RF circuit module **74***a* in a second series signal path **73***a*.

In the case where beamformer board **68** is used in a transmit/receive antenna system, the circuit module **74** may be provided as a transmit/receive (TR) module, which thus allows transmission of RF signals from a transmitter (not shown) through beam ports **69***a*–**69**NB to the RF antenna elements **72** and also allows received RF signals to propagate from antenna elements **72** to ports **69***a*–**69**NB and subsequently to a receiver (not shown). Alternatively still, in the case where the antenna system **70** is a transmit only system, RF circuit module **74** may be provided as a power amplifier.

A plurality of beamformer boards **68** may be appropriately coupled as described above in conjunction with FIG. **1** to thus provide a planar phased array antenna system. The phase shifter settings may be appropriately selected as discussed above in conjunction with FIG. **1** to provide a plurality of independently steered beams.

Referring now to FIG. **4**, a beam/element grid junction **100** having ports **100***a*–**100***d* includes a first transmission line **102** having a first end coupled to port **100***a* and having a second end coupled to a coupling element **104**. In this particular example, coupling element **104** is provided as a directional coupler **104** having a first port **104***a* coupled to the second of transmission line **102**. Ideally, coupler **104** has the property that in response to a signal incident at port **104***a* the coupler couples power to ports **104***b*, **104***c* but not into port **104***d*. Thus, with port **104***a* corresponding to an input port, port **104***d* is said to be uncoupled or isolated from port **104***a*.

Similarly, in response to a signal incident at port **104***b*, the coupler **104** couples power to ports **104***a* and **104***d* but not into port **104***c*. Thus, with port **104***b* corresponding to an input port, port **104***c* is said to be uncoupled or isolated from port **104***b*.

Coupler port **104***b* is coupled to a first port **108***a* of a phase shifter **108** and a second phase shifter port **108***b* is coupled to a first port **110***d* of a second directional coupler **110**. Ideally, coupler **110** has the property that in response to a signal incident at port **110***d*, the coupler **110** couples power to ports **110***b* and **110***c* but not into port **110***a*. Thus, with port **110***d* corresponding to an input port, port **110***a* is isolated from port **110***d*.

Similarly, in response to a signal incident at port **110***c*, the coupler couples power to ports **110***a*, and **110***d* but not into port **110***b*. Thus, with port **110***c* corresponding to an input port, port **110***b* is said to be uncoupled or isolated from port **110***c*.

Termination **112** is coupled to ports **104***d* and **110***b*. A transmission line **114** has a first end coupled to coupler port **110***c* and a second end coupled to element junction port **100***d*.

When element junction **100** is included in a transmit array antenna, the element junction **100** operates in the following manner. A transmit signal incident at port **100***d* propagates along signal path **114** to coupler port **110***c*. The signal is coupled to ports **110***d* and **100***a* while port **110***b* is isolated from port **110***c* and thus, no signal propagates thereto. In a practical coupler, however, a portion of the energy is coupled to port **110***d* and thus, termination **112** terminates any energy propagating to port **110***b*. The portion of the signal coupled to port **110***a* is fed to element junction port **100***b* and may be either terminated or possible fed to a signal path such as signal path $30_{a,1}$ described above in conjunction with FIG. **1**. The portion of the signal coupled to coupler **110***d* is coupled through phase shifter **108** which provides a predetermined phase shift to the signal and is subsequently fed to an input port **104***b* of coupler **104**. The signal provided to port **104***b* is coupled between ports **104***a* and **104***d* with port **104***c* being isolated. The termination **112** terminates the energy propagating from port **104***b* to port **104***d*. The signal propagating to port **104***a* is coupled through transmission line **102** to grid element junction port **100***a* and possibly fed to a transmit antenna element such as element **12** described above in conjunction with FIG. **1** or to a signal path such as one of the signal paths described above in conjunction with FIG. **1**.

In a receive mode of operation, the receive signal (e.g. from a receive antenna element or from a signal path such as one of the signal paths **20** described above in conjunction with FIG. **1**) is fed to element junction port **100***a* through signal path **102** to port **104***a* of coupler **104**. The signal is coupled from port **104***a* to ports **104***b* and **104***c* with port **104***d* being isolated. Ideally, no signal should appear at isolated port **104***d*. In a practical coupler, however, a portion of the signal appears at port **104***d* and thus the termination **112** terminates this energy. The signal at port **104***c* propagates to element junction grid port **100***c* and may be either terminated or possibly fed to a signal path such as one of the signal paths **20** described above in conjunction with FIG. **1**. The signal fed to port **104***b* is coupled through phase shifter **108** which introduces a predetermined phase shift and is subsequently coupled to port **110***d* of coupler **110**.

The signal is coupled from port **100***d* to ports **110***b*, **110***c* of coupler **110** with port **110***a* being isolated. The termination **112** terminates the signal propagating at port **110***b* and the signal coupled to port **110***c* propagates through transmission line **114** to element grid junction port **100***d* and may be fed to a receiver, another signal path, a signal combiner or to another processing circuit for further processing. It should be noted that in a transmit mode of operation, transmit signals fed to grid/element junction port **100***d* do not propagate toward grid/element junction port **100***c* since coupler port **104***c* is isolated from coupler port **104***b*.

Similarly, in a receive mode of operation, receive signals fed to grid/element junction **100***a* do not propagate toward grid/element junction port **100***b* since coupler port **110***a* is isolated from coupler port **110***d*.

It should also be noted that in some embodiments it may be desirable to insert amplitude adjust elements on either side of phase shifter **108** or in the appropriate signal paths between transmission line **114** and coupler port **110***c* or between transmission line **102** and coupler port **104***a* or at any of the appropriate ports of couplers **104**, **110** or at any of the grid element junction ports **110***a*–**100***d*. In this manner, element grid junction can provide both amplitude and phase control of signals fed thereto. It should further be noted that DC power and control lines have been omitted for clarity but that phase shifter **108** may be provided as a commercially available phase shifter which operates at the desired frequency and which provides the requisite phase shift and that those of ordinary skill in the art understand how to provide power and control signals to such devices.

Referring now to FIG. **5**, an alternate implementation of an antenna system having the same independent beam characteristic as antenna system **10** in FIG. **1** is shown. FIG. **5** shows a two-dimensional or planar phased array antenna system **10'** capable of forming multiple, independently steered antenna beams includes a plurality of antenna elements generally noted **12'** disposed to provide a planar array antenna **13'**. The antenna system **10'** includes array columns **14'***a*–**14'**N_C, generally denoted **14'**, array rows **16'***a*–**16'**N_R, generally denoted **16'** and rowboards **15'**. The plurality of antenna elements **12'** are thus arranged as an array having NC columns and NR rows as described above in conjunction with FIG. **1**.

Each of the plurality of rowboards **15'** in the array **13'** may be provided as a multi-layered printed circuit board. Each row board **15'** forms N_B fan beams from the N_C antenna elements of each row. The antenna **10'** is thus similar to antenna **10** described above in conjunction with FIG. **1**. Antenna **10** in FIG. 1 utilized series feed signal paths **20**, **30** and couplers $\mathbf{22}_{i,j}$, $\mathbf{26}_{ij}$ to provide properly amplitude adjusted signals which are combined to form antenna beams. Antenna **10'** of FIG. **5** on the other hand, includes a corporate power divider **120** which receives signals from low noise amplifier **18'** at an input port **120***a* and distributes the power at a plurality of output ports **121***a*–**121**NB. Each of the output ports **121***a*–**121**NB feeds a respective one of phase shifters $\mathbf{24'}_{1,1}$–$\mathbf{24'}_{NB,NC}$. It should be noted that in the embodiment of FIG. **5**, no couplers are needed between the feed line **120** and the phase shifters **24'**.

Selected groups of phase shifters $\mathbf{24'}_{1,1}$–$\mathbf{24'}_{1,NC}$ feed corresponding ones of a plurality of signals to signal combiners **124***a*–**124**NB. In some embodiments, it may be desirable to provide signal combiners **124***a*–**124**NB as isolating combiners with isolation resistors. Here, for clarity, only a single combiner **124***a* is shown. The signals are fed from phase shifters **24'** through optional RF feedthrough circuits **28'** to respective input ports of the signal combiner **124***a* at input ports **123***a*–**123**N_C. Signal combiner **124***a* combines the signals fed to the input ports thereof and provides a combined output signal at an output port **126***a* which is the fan beam number **1** used to form pencil beam **1**. This output corresponds to output $\mathbf{34}_{a,1}$ of FIG. **1**. The output port **126***a* is coupled to an input port of a second combiner, **40***a'*, at a respective input port **39***a'* thereof. The combiner **40'** combines the signals fed thereto at an output port **41***a'* at which an antenna beam (i.e. beam number **1**) having a pencil beam shape is provided. This output **41***a'* corresponds to output **41***a* of FIG. **1**.

In one particular embodiment, divider **120** is provided as a corporate power divider **120** having a single input port and 64 output ports (e.g. a 1 to 64 corporate divider). Each of the 64 output ports are coupled to a respective one of 64 phase shifters. Thus, the divider **120** drives 64 sets of phase shifters **24'**. The phase shifter feed signals to a 64 to 1 corporate combiner used to form 64 antenna fan beams on row board **15'** (designated row board number **1**) as well as the other row boards.

Thus, antenna **10'** utilizes parallel feed signal paths and power dividers. This in contrast to use of a series feed signal paths and couplers as described above in conjunction with FIG. **1**.

Also, to combine the outputs of the phase shifters $\mathbf{24'}_{1,1}$ and $_2$, $\mathbf{24'}_{1,NC}$ utilize a plurality of 64 to 1 corporate combiners **124** in contrast to the series feed signal paths **30** and couplers described above in conjunction with FIG. **1**. It should also be noted that in the embodiment of FIG. **5**, no couplers are coupled to the phase shifter circuit inputs or outputs as was the case in FIG. **1**.

Referring briefly to FIG. **5**A, a corporate divider **130** having an input port **130***a* and a plurality of output ports **131***a*–**131***h* is here shown as a 1 folded to 8 corporate divider provided from a plurality of power divider circuits **132***a*–**132***g*. By providing the power divider **130** in a folded configuration, the divider is able to fit within the area available between the columns of the antenna elements **12** by reducing the width of the corporate dividers **120** and to reduce the height of the beamformer boards behind the array if desired by reducing the width of the corporate combiners **124**. A divider similar to corporate divider **130** having an appropriate number of ports may be used to provide the divider and combiner circuits **120**, **124** described in conjunction with FIG. **5**. To maintain the compactness of the row boards, corporate divider **130** may include an RF feedthrough to couple signals from a first RF layer to a second RF layer.

With respect to implementing the 64 antenna beam embodiment mentioned above, a printed circuit board using two circuit layers may be required to implement a 1 to 64 divider. Each layer could include a 1 to 8 folded corporate divider similar to divider **130** with an RF feedthrough used to provide and RF signal path from a first RF layer to the a second RF layer on the printed circuit board.

If desired, the 64 to 1 horizontal combiner **124** (FIG. **5**) can be implemented in a single layer since the available space is not constrained by the spacings between antenna elements **12'** (FIG. **5**) and the board may not be constrained in height. If the board is constrained in height, then two layers circuit layers could be used to provide a compact assembly.

It should be noted that the antenna architecture described above in conjunction with FIG. **5** has the advantage that the phase shifter settings for the i^{ith} beam are independent of that

from the j^{th} beam, as was the case for the implementation of FIG. 1. The implementation of FIG. 5, furthermore, has the advantage that the phase shifter amplitude and phase errors as well as losses do not cascade. To form a beam, the signal from one antenna element propagates through only one phase shifter to form a beam before the signals for that beam are summed. Hence, the implementation of FIG. 5 is an inherently low loss implementation.

This implementation also has the advantage that the failure of one phase shifter only effects a single beam as a failure of only one element. Finally, for the implementation of FIG. 5, there is no coupling between the antenna beams. The power from beam i does not couple to beam j as it does in prior art techniques.

Although the implementation described above in conjunction with FIGS. 5 and 5A is for a receive array antenna, the technique described can just as well be used for a transmit array antenna.

It should also be noted that another feature of the embodiments of FIGS. 1, 2 and 5 above is the use of row boards perpendicular to the array to form independent fan beam outputs which are combined by column boards to finally form the independent pencil beams. This leads to a relatively easy construction of the multiple beam array antenna.

Referring now to FIG. 6, a beamformer board **150** for use in a transmit antenna system includes a plurality of beamports **152***a*–**152**NB generally denoted **152** and a plurality of antenna element ports **154***a*–**154**NC generally denoted **154**. Each of the antenna element ports have a respective one of a plurality of antenna elements **170***a*–**170**NC generally denoted **170** coupled thereto.

Beamformer board **150** includes an amplifier circuit **156** which receives signals at input ports **152***a*–**152**NB and provides amplified output signals to respective ones of a plurality of signal paths **158***a*–**158**NB generally denoted **158**. In one embodiment, amplifier circuit **156** is provided from a plurality of power amplifiers **156***a*–**156**NB.

A coupling element **160** couples a portion of the signal propagating along series signal path **158***a* to series signal path **162***a*. Coupling element **160** is disposed such that the phase shift introduced by the coupling element **160** into the signal coupled from signal path **158***a* to signal path **162***a* effects only a single antenna beam. This allows circuit **150** to be used to provide an antenna system which produces multiple independently steered beams.

The coupling element **160** may be provided, for example, as a beam/element grid junction similar to beam/element grid junction **100** described above in conjunction with FIG. 4. Those of ordinary skill in the art will appreciate of course that there are a variety of different ways in which the coupling/phase shifting function provided by coupling element **160** may be implemented.

In this case coupling element **160** includes a pair of line couplers **164** which may be provided as stripline, or microstrip couplers, for example, coupled to a phase shifter circuit as shown. It will be appreciated, of course, that the couplers **164** may be provided using any technique well known to those of ordinary skill in the art.

The signal fed from coupling element **160** to the signal path **162***a* propagates along the signal path **162***a* through a delay line **168***a* to beamformer port **154***a* and is subsequently emitted through antenna element **170***a*.

In addition to serial feed signal paths, **158**, **162**, beamformer board **150** may include parallel feed signal paths such as signal paths **172**, **174**. Parallel feed signal path **172** has an input port **172***a* coupled to a first end of signal path **176**. A second end of signal path **176***a* is coupled to a first end of a delay **168***i*. A second end of the delay line **168***i* is coupled to port **154***i* and subsequently to antenna element **170***i*. Parallel feed circuit **172** also includes a plurality of output ports **173***a*–**173**NB. Each of the output ports are coupled a respective one of phase shifter circuits **180***a*–**180**NB.

Parallel feed signal path **172** includes a plurality of power divider circuits **178** coupled as shown to provide a 1 to NB power division. The power split of each power divider is selected to provide a particular weighting from each of the beam input ports **152***a*–**152**NB.

Coupled along each of the signal paths **158** are delay lines **182**. The delay lines **182** are used to provide a predetermined phase compensation between each of the ports **154**. The delays are used to compensate for delay dispersion across a row of the array when needed.

Parallel feed signal path **174** likewise includes a plurality of power divider circuits **186***a*–**186**NC generally denoted **186**. Output ports **175** of power divider **174** are coupled to respective ones of phase shifters **168***a*–**168**N_C as shown. When using the parallel feed **174** the delays **168** and **182** are not needed.

An embodiment of an array can use either serial feed circuits for paths **158** and **162** (thus yielding the embodiment of FIG. 1) or series feed circuits for path **158** and corporate feed circuits (e.g. a circuit similar to circuit **172**) for path **162** or vice versa, or a corporate feed circuit (e.g. a circuit similar to circuit **174**) for feed circuit **158** and for **162** a corporate feed circuit (e.g. a circuit similar to circuit **172**) to yield the embodiment of FIG. 5.

A plurality of beamformer boards **150**, may be appropriately coupled as described above in conjunction with FIG. 1 and FIG. 5 to thus provide a planar phased array antenna system. The phase shifter settings may be appropriately selected as discussed above in conjunction with FIG. 1 to provide a plurality of independently steered transmit antenna beams.

Referring now to FIG. 7, an antenna array **200** includes a first printed circuit board **202** having a plurality of antenna elements **204** disposed thereon in an array pattern to thus provide an array of antenna elements **205**. Array element board **202** is disposed over an optional element module interface board **206**. Element module interface board **206** (if needed) provides a mechanical and electrical interface between the antenna array **205** on array element board **202** and feed circuits disposed on row boards **208***a*–**208**NR generally denoted **208**.

In this particular embodiment, each of the row boards **208** is provided from a plurality of RF subarrays **210***a*–**210**K. Coupled to each of the row boards **208** is a corresponding one of a plurality of column boards **212***a*–**212**NB generally denoted **212**. In one particular embodiment, the array of antenna elements **205** included in antenna system **200** is provided as an array of 75 columnsx75 rows of antenna elements which are coupled to row boards **208** and column boards **212** to produce 8 independently-steered antenna beams. Thus in this case, 8 column boards **212** are required (i.e. NB=8) and 75 row boards **208** are required (i.e. NR=75).

To provide the antenna system **200** having 64 beams and a 75x75 antenna array elements, five RF subarrays **210***a*–**210***k* each having 15 column elements and capable of producing 8 beams are coupled together to provide a single row board **208**. Thus in this case, K is equal to five in FIG. 7.

Taking RF subarray **210K** as representative of each of the RF subarrays **210**, each of the RF subarrays includes a plurality of phase shifters **216** having a number of bits selected to provide a predetermined desired phase shift. For example, the phase shifters **216** may be provided as three bit phase shifters to provide a phase shift of 0° to 360° degrees in 45° steps.

The RF subarrays **210** may be provided from channeled microstrip on LTCC with transmission lines **230**, **240** provided as embedded waveguides or strip line transmission lines.

Mating devices **220** provide connections between each of the subarrays **210***a*–**210K**. Mating devices **220** may be provided as waveguide, microstrip, coaxial or bond connections between each of the subarrays **210**.

When antenna system **200** is provided having an operating frequency in the range of about 20 to about 30 gigahertz, and the antenna is manufactured using the aforementioned channelled microstrip on LTCC, a 75x75 element antenna array is provided having a length L_1, of about 20 inches, a height H_1 typically of about 2.5 inches, and a width W_1 typically of about 20 inches.

With each RF subarray **210** provided having 15 elements and 8 beams, the physical size of the subarray is about 4 inches in length, about 2.5 inches in height and about 0.15 inches in thickness and had a weight of about 0.1 pounds.

It should be noted that in this particular view, circuitry to provide DC power and array control is omitted for clarity.

Referring now to FIG. **7A**, an enlarged portion of a section of subarray **210** is shown. In this enlarged view, phase shifters **216** are more clearly shown, disposed on the first transmission line **230** with the second transmission line **240** orthogonally disposed with respect to the first transmission line **230**. In this manner, a plurality of crossed series feed circuits are provided. The transmission lines **230**, **240** can be provided as imbedded waveguide or strip line transmission lines which present a relatively low insertion loss characteristic to signals propagating therein.

Referring now to FIG. **7B**, a cross-sectional view taken along a central longitudinal axis of transmission line **240** and across a transverse axis of phase shifter **216** and transmission line **230** is shown. A substrate **240** has disposed thereover a first conductor **249** and a plurality of conductive walls **250** which form a channeled microstrip transmission line **252**. Disposed in the channeled microstrip transmission line are the phase shifters **216**.

Each of the phase shifters **216** is coupled to a coupling loop **254** which is disposed in the embedded waveguide or strip line transmission lines **240**. Coupling loop **254** includes a pair of posts **254** and a connecting member **256**. Coupling loop **255** couples energy from the transmission line **240** to the phase shifter **216** such that a phase shift is introduced into a signal fed to the phase shifter **216**. The transmission line **240** is disposed over a transmission line media **260** which is spaced between waveguides **230** and through which DC and logic wires or lines **264** are disposed.

Referring now to FIG. **7C**, a cross-sectional view through a central longitudinal axis of transmission line **230** and across a transverse axis of the transmission line **240** is shown. Phase shifters **216** are disposed above a conductor **249**. Coupling loops **254**, **268** are disposed to couple energy from respective ones of the transmission line **230**, **240**. Coupling loops **268** include a pair of posts **270** and a connecting member **272**. Coupling loops **268** couple energy from the transmission line **230** to the phase shifters **216** such that a phase shift is introduced into a signal fed to the phase shifter **216**. In this particular implementation, transmission line **240** can provide a beam waveguide transmission line and transmission line **230** can provide an element waveguide transmission line.

Referring now to FIGS. **8** and **8A** in which like elements are provided having like reference designations, a portion of a grid/element junction implemented using dielectric filled ridge waveguide is shown. FIG. **8** is a broken cross-sectional view of a ridge element waveguide **300** and a ridge beam waveguide **360** and FIG. **8A** is a perspective view of the ridge element waveguide **300** and the ridge beam waveguide **360**.

Turning now to FIGS. **8** and **8A**, element waveguide **300** having sidewalls **301** and a ridge **302** is disposed over a dielectric slab **304**. Dielectric slab **304** has a plurality of conductors **308** disposed thereon with each of the conductors **308** having a pair of conductive posts **310***a*, **310***b* coupled thereto. Conductors **308** provide an electrical connection between the posts **310***a*, **310***b*. Conductors **308** and posts **310***a*, **310***b* form a coupling loop **311** (FIG. **8A**). As can be seen in FIG. **8A**, in a preferred embodiment, conductor **308** is disposed along a central longitudinal axis of waveguide **300**.

A conductive bond film **306** adheres the sidewall **301** of waveguide **300** to a conductive surface **312** which forms the bottom wall of the waveguide **300**. The conductive surface **312** is disposed over a first surface of the dielectric slab **304**. Conductive surface **312** may be formed a number of different ways. For example, as illustrated in FIG. **8**, conductive surface **312** may be provided as a conductive layer (e.g. a sheet of appropriately processed or treated copper or other conductive material) adhered or otherwise disposed on the surface of dielectric slab **304**. Alternatively, as illustrated in FIG. **8A**, conductive surface **312** can be formed by plating stripline circuit board **313** (FIG. **8A**).

Conductive surface **312** is disposed over a dielectric layer **314** having an opening **316** therein. Disposed in opening **316** is a phase shifter integrated circuit chip **320** which is coupled via a bond wire **322** to a signal path **317**. The signal path **317** is here provided as a conductor disposed over a first surface of a dielectric **326** having a conductive layer **328** disposed over a second opposing surface thereof. Conductive layers **312** and **328** correspond to ground plane layers and layer **317** corresponds to a circuit layer in which radio frequency (RF) (including microwave and millimeter wave) signals can propagate.

Disposed under the conductive layer **328** is a second dielectric layer **330**. A conductive layer **331** in which DC and logic signals may propagate is disposed over a surface of dielectric **330**. A dielectric layer **332** is disposed over layer **331** and a ground plane layer **334** is disposed over layer **332**. A dielectric slab **340** having a plurality of conductors **338** disposed thereon is disposed over layer **334**. A pair of conductive posts **342** (only one post **342** being visible in FIG. **8**) are disposed through dielectric slab **340** and conductor **338** provides an electrical connection between the posts **342**. Conductor **338** and posts **342** thus form a coupling loop **341** (FIG. **8A**).

Dielectric **304**, conductor **312**, couplers **311**, dielectric **314**, conductor **317**, dielectric **326**, conductor **328**, dielectric **330**, conductor **331**, dielectric **332**, conductor **334** and conductor **338**, dielectric **340** and coupling loop **341** form a microwave circuit assembly **350**. The microwave circuit assembly **350** is disposed over the beam waveguide **360** which is provided as a ridge waveguide **354** formed by surfaces of waveguide walls **354***a*, **354***b*, **354***d* and surfaces

of ridge **354***c* as shown in FIG. **8**. The conductive layer **334** thus forms a wall of the waveguide **354**.

It should be noted that, in an effort to promote clarity in the description, only a limited number of circuit layers are shown in FIGS. **8** and **8**A. In some applications it may be desirable or even necessary to utilize additional circuit layers. Such additional circuit layers may be desired or required to provide signal paths for transmission of, for example, DC and logic signal. Those of ordinary skill in the art, after reading the description hereinbelow will appreciate how, why and when to add additional circuit layers and the purpose of the additional circuit layers. Also, to show alternate techniques for implementing the circuits, it should be noted that there are slight differences between the implementations of FIG. **8** and FIG. **8**A.

A pair of conductive layers **352***a*, **352***b* which may be provided as conductive bond films similar to conductive bond film **306** are disposed over waveguide walls **354***a*, **354***b*. When assembled, the dielectric slab **340** is disposed in an internal portion of the waveguide **354** and thus provides beam waveguide **360** as a dielectric loaded ridge waveguide **354**. The upper assembly provided by beam waveguide **360**, microwave circuit assembly **350** and upper element waveguide **300** is repeated on the lower portion of beam guide **360** as indicated in FIG. **8**.

In general overview, coupling loops **311**, **341** couple energy from a first one of the waveguides **300** and **360** through the phase shifter **320** to a second one of the waveguides **300** and **360**. The operation of coupling loops **311**, **341** and phase shifter **320** can be more easily explained with reference to FIG. **8**A. It should be noted that the exemplary implementation described in conjunction with FIG. **8**A is only illustrative and should not be construed as limiting.

As can be seen in FIG. **8**A, signals propagating in the dielectric-loaded waveguide **300** are coupled by coupling loop **311**. Printed circuit board **313** is provided as a multilayer printed circuit board having conductive surfaces **312**, **312***a*. The printed circuit board **313** includes a transmission line **362**. A first end of the transmission line **362** is coupled through an RF feedthrough **364** to the post **310***a* of coupling loop **311**. The posts **310***a*, **310***b* may be formed as plated through holes in dielectric **304**. Thus, care must be taken not to provide a short circuit signal path between post **310***a* and conductive surface **312**. This may be accomplished, for example, by removing conductive material from the region where the RF feedthrough **364** mates with the conductive post **310***a*. Conductive post **310***b* is coupled to a termination.

A second end of transmission line **362** is coupled to a second transmission line **366** which leads to transmission line **317**. The bond wire **322** or other appropriate electrical connection couples the signal path **317** to phase shifter **320**. It should be noted that transmission line **362** is provided as a stripline transmission line while transmission line **366** is provided as a microstrip transmission line. Thus a stripline-to-microstrip transition is required to provide a relatively well-matched, low insertion loss connection between the signal paths **362**, **366**. Similarly, a second bond wire **322** couples phase shifter **320** to coupling element **341** as shown. Thus signals propagating in waveguide **300** may be coupled via coupling loop **311** through phase shifter **320** and into waveguide **360** via coupling loop **341**.

Referring now to FIG. **9**, a dielectric-loaded ridge waveguide **370** includes waveguide **372** having a ridge **374** disposed along a central longitudinal axis thereof. A dielectric loading material **376** is disposed on an inner wall of waveguide **372**. Disposed on a lower portion of dielectric **376** is a strip conductor **378** here provided having an oval shape. A pair of conductive posts **380***a*, **380***b* are disposed through the upper waveguide wall **372***a* and through dielectric **376** and contact the conductive strip **378**. The conductive posts and conductive strip **378** form a coupling element **385**. The conductive post **380***a*, **380***b* may be provided, for example, as plated through holes.

Coupling element **385** may be used, for example, in the phased array antenna systems described above to couple energy from the waveguide transmission lines of FIGS. **8** and **8**A into phase shifters as described above.

Having described preferred embodiments of the invention, it will now become apparent to one of ordinary skill in the art that other embodiments incorporating their concepts may be used. It is felt therefore that these embodiments should not be limited to disclosed embodiments, but rather should be limited only by the spirit and scope of the appended claims.

What is claimed is:

1. An RF circuit comprising:

a first directional coupler having a first port, a second port, a third port and a fourth port;

a phase shifter having a first port coupled to the third port of said first directional coupler and having a second port;

a second directional coupler having a first port coupled to the second port of said phase shifter and having a second port, a third port and a fourth port;

an antenna element coupled to the first port of said first coupler;

a first termination coupled to the second port of said first directional coupler; and

a second termination coupled to the third port of said second directional coupler.

2. The RF circuit of claim **1** further comprising a transmitter coupled to the fourth port of said second directional coupler.

3. The RF circuit of claim **2** further comprising:

a first signal path coupled between said antenna element and the first port of said first coupler; and

a second signal path coupled between the fourth port of said second directional coupler and said transmitter.

4. The RF circuit of claim **3** further comprising:

a signal combiner having an input port coupled to the second end of said second signal path and having an output port; and

a receiver having an input port coupled to the output port of said signal combiner.

5. The RF circuit of claim **1** further comprising a further directional coupler connected to the second port of the second directional coupler.

6. The RF circuit of claim **1** further comprising a further directional coupler connected to the fourth port of the first directional coupler.

7. A system for steering multiple antenna beams independently, comprising:

first, second, third, and fourth RF circuits each including

a first directional coupler having a first port, a second port, a third port and a fourth port;

a phase shifter having a first port coupled to the third port of said first directional coupler and having a second port;

a second directional coupler having a first port coupled to the second port of said phase shifter and having a second port, a third port and a fourth port;

an antenna element coupled to the first port of said first coupler;

a first termination coupled to the second port of said first directional coupler; and

a second termination coupled to the third port of said second directional coupler,

wherein the second port of the second directional coupler of the first RF circuit is coupled to the fourth port of the second directional coupler of the second directional coupler, the fourth port of the first directional coupler of the first RF circuit is coupled to the first port of the first directional coupler of the third directional coupler, the fourth port of the first directional coupler of the second RF circuit is coupled to the first port of the first directional coupler of the fourth RF circuit, and the second port of the second directional coupler of the third RF circuit is coupled to the fourth port of the second directional coupler of the third RF circuit.

8. The system according to claim **7**, wherein the respective antenna elements form an array having a plurality of columns and a plurality of rows.

9. The system according to claim **8**, wherein the respective antenna elements provide a phased array.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 6,232,920 B1
DATED : May 15, 2001
INVENTOR(S) : Brookner et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 1,
Line 5, delete "is continuation" and replace with -- is a continuation --.
Line 12, delete "1. Field of the Invention" and replace with
-- FIELD OF THE INVENTION --.
Line 15, delete "2. Background of the Invention" and replace with
-- BACKGROUND OF THE INVENTION --.
Line 39, delete "of a" and replace with -- of as a --.

Column 3,
Line 35, delete "to second" and replace with -- to a second --.
Line 37, delete "paths coupled" and replace with -- paths is coupled --.
Line 37, delete "plurality a" and replace with -- plurality of --.
Line 48, delete "i^{ith}" and replace with -- i^{th} --.

Column 5,
Line 4, delete "1a-14N" and replace with -- 14a-14N --.

Column 6,
Line 6, delete "circuit 20" and replace with -- circuit $20_{a,1}$ --.
Line 13, delete "$24_{a,1}$" and replace with -- $24_{1,1}$ --.
Line 28, delete "$12_{1,3}$-20_{NC} " and replace with -- $12_{1,3}$-$20_{1,NC}$ --.

Column 10,
Line 31, delete "100a" and replace with -- 110a --.
Line 37, delete "possible fed" and replace with -- possibly fed --.

Column 11,
Line 1, delete "100d" and replace with -- 110d --.

Column 12,
Line 63, delete "layers circuits layers" and replace with -- circuit layers --.
Line 67, delete "i^{ith}" and replace with -- i^{th} --.

Column 14,
Line 64, delete "210a-210k" and replace with -- 210a-210K --.